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SYMPOSIUM ON FISHERIES ACOUSTICS

Bergen, Norway, 21-24 June 1982

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

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FAO Fisheries Report No. 300 FIRM/R300

SYMPOSIUM ON FISHERIES ACOUSTICS

Selected papers of the
ICES/FAO Symposium on Fisheries Acoustics
Bergen, Norway, 21-24 June 1982

Edited by

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Fishery Resources and
Environment Division

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome 1983

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PREPARATION OF THIS DOCUMENT

This publication contains a selection of the contributions given to the Symposium on Fisheries Acoustics held in Bergen, Norway, 21-24 June 1982. The Symposium was organized by the International Council for the Exploration of the Sea (ICES) in collaboration with FAO.

Out of 117 accepted contributions only 97 were actually presented at the Symposium. Most of these papers were sent to the participants well before the Symposium. For each of the 13 topics a specialist was appointed as rapporteur to present a critical summary of the papers assigned to his topic.

ICES will publish a report of the Symposium, including the four invited review papers (Nos. 1 to 4), the presentation of the rapporteurs and summaries of the discussions. That document, edited by the Symposium's convener, Mr. R.E. Craig, will be published in 1984 as Rapp.P.-V.Réun.CIEM. 184.

In November 1982 it was decided that FAO would publish a document of selected contributions and Messrs. O. Nakken and S.C. Venema were appointed editors. To assist in the selection process the rapporteurs and chairmen of the Symposium were requested to submit their opinion of each contribution. Twelve persons, to which the editors are most grateful, responded to the request. The selection of the 36 papers contained in this document is based on the opinions of these persons and the editors.

In the present document the contributions are grouped in a similar way as at the Symposium. The references of all papers have been combined and are presented at the back of the document.

A list of papers presented but not included in this document is given in Appendix I, where information is also provided on those papers already published elsewhere. Some contributions dealing with new developments in instrumentation will be published later in the form of an FAO Fisheries Circular, edited by Mr. R.B. Mitson.

Most of the 36 papers contained in this document were retyped at the Institute of Marine Research in Bergen, Norway, by Mrs. Gunn Farstad, Mrs. Wenche Meidell, Mrs. Gunvor Christensen, Mrs. Jessie Pereira and Mrs. Edel Vetaas. At FAO the references were checked by Ms. Gloria Soave and typed by Ms. Doris Dearing. Mrs. Yvette Corsetti, Mrs. Françoise Schatto-Terribile, Miss Gianna Landi and Dr. S.M. Garcia assisted in the final preparation.

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ABSTRACT

This document contains 36 of the 97 papers presented at the ICES/FAO Symposium on Fisheries Acoustics held in Bergen, Norway, 21-24 June 1982. The papers have been arranged by main topics, dealing with general definitions, physical principles, including the acoustic beam size, calibration of equipment, target strength studies, school and multiple echoes, data handling, survey results and application, comparisons with results from other data, statistics and design of surveys. A list of other papers presented at the Symposium is included.

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RE-DEFINITION OF SONAR THEORY IN TERMS OF ENERGY

by

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ABSTRACT

The definition of sonar theory in terms of energy instead of power is discussed. There are several advantages both in comprehensibility and simplification of such a shift. Basic textbooks and training manuals should therefore be considered rewritten in terms of energy units.

RESUME

Le definition d'une theorie du sonar en termes d'énergie au lieu de puissance est discutée. Cette modification presente plusieurs avantages du point de vue de la comprehension et de la simplification. On doit donc envisager de recrire les manuels de base et de vulgarisation en termes d'unités d'énergie.

1. In connection with the meeting on Hydroacoustical Methods for the Estimation of Marine Fish Populations, held in Cambridge, Massachusetts, in 1979, the author was invited to provide a contribution on "Units, Symbols and Definitions in Fisheries Acoustics" (Craig, 1981).

Following the accepted ideas of the time, which have a long history, the whole detection process was described in terms of power.

In discussing the action of pulsed sonars, which continue to be the most important, it is equally possible to describe this detection process in terms of energy rather than power. Writing in 1982, it must be recognised that a new generation of physicists wish to define target strength in terms of the reflected energy, largely because the available acoustic theory allows them to calculate the strength of standard targets on this basis. There is the further advantage that definition in terms of energy is more directly related to the process of echo-integration.

2. To make the matter perfectly clear to the non-physicist, if an acoustic power of one of one watt continues for one second, the energy involved is one watt-second, normally called one Joule. Thus in terms more related to sonar, a transmission of one kilowatt for one millisecond also represents an energy of one Joule. Since normally the power in a pulse rises to a peak, then falls away, the situation is that

$$\text{energy} = \int(\text{power})dt$$

over the period occupied by the pulse. If reference is made to Fig. 1 it will be seen that the energy is the area under the power curve.

A minor advantage of a shift to energy as the basis of our subject, is that there is no tradition among engineers of measuring energy in decibels. This could aid in getting rid of the decibel, a notation whose main effect has been to confuse non-physicist.

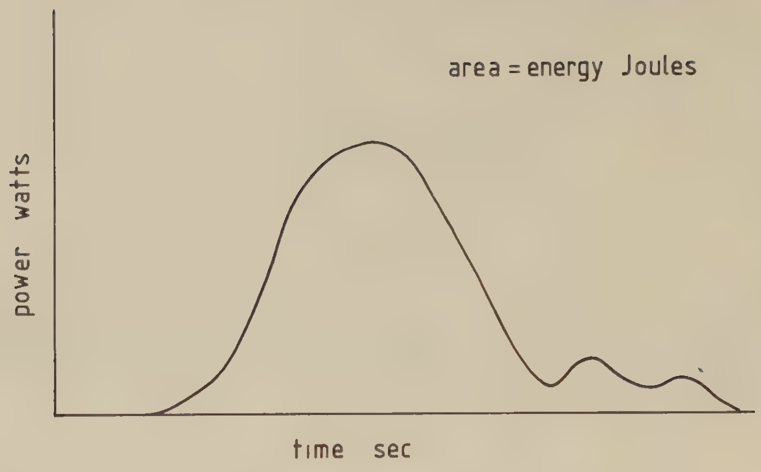

Fig. 1

3. In this paper, the author follows the step-by-step argument of the 1979 paper, making the fewest possible linguistic changes and keeping the original symbols with changed meaning. He hopes this will be easier to follow than the introduction of a new symbolism. The paragraph numbering has been matched to the earlier paper.

4. For "acoustic intensity" substitute pulse intensity. The pulse intensity at any point being represented by I and measured in Joules per square metre ($J\ m^{-2}$).

5. For "source level" substitute pulse source level (PSL). The pulse source level of a pulsed acoustic source is represented by S and is measured in Joules per steradian ($J\ sr^{-1}$) and this accords with the well-known relation

$$I = SR^{-2}\ e^{-\alpha R}$$

where R is the range in metres and α is the attenuation coeffcient.

As in the previous notation, where the system has a recognised axis, we can define an axial PSL. S_o noting that in some non-axial direction the source level is S where $S/S_o = b_1$ and b_1^o is the transmitter directional factor.

6. The term "receiver sensitivity" retains its original meaning, the re-definition specifying that the receiver sensitivity in any direction is the receiver output in Joules, per unit pulse intensity incident from that direction. It is measured as (Joules) per (Joule per square metre) ie simply as m^2 as before.

The nominal output energy from the receiver will, however, be expressed as ($volts^2$ seconds) consistently through all calibration and operation.

7. The target strength also remains unaffected by the change to a new definition. If a target encounters a pulse intensity I and responds as a secondary source of PSL = S' the target level is given by $T = S'/I$. The definition expresses T as (Joules per steradian) per (Joule per square metre) ie as $m^2\ sr^{-1}$ as before.

8-9. The sonar equations for a single target remain entirely unaffected by the change to energy units.

10. The definitions of "volume scattering coefficient" and "area scattering coefficient" are entirely unaffected by the change to energy units.

We may note that the standard approach to the measurement of the volume scattering coeffcient s_v, and hence to the principles of echo-integration, needs to be re-stated, since the pulse length τ and the so-called "pulse volume" have been eliminated from the formal argument (useful though they remain for visualizing some aspects of echo detection).

11. Consider the hemispherical shell lying between ranges R and R + dR. An element of volume in this shell corresponding to a small element da of solid angle is $R^2 dRda$. With a voltage linear (20 logR) TVG, the output energy from the receiver due to this element is $s_v \, S_o \, K_{ol} \, B \; dR \; da$. Thus the output energy due to the whole shell is

$$s_v \, S_o \, K_{ol} \, A \; dR$$

where $A = \int B \, da$ is the effective beam angle for integration exactly as before, and the output energy deriving from targets between the ranges R_1 and R_2 is simply

$$C = s_v \, S_o \, K_{ol} \, A \, [R_2 - R_1]$$

In this equation s_v is the average value of the volume scattering coefficient between the range limits and within the effective beam angle A though there is of course some extra weighting given to the central part of the beam. The equation applies to the received energy from a single pulse, and the average for many pulses will of course be taken to derive the average value of s_v which is related to the organisms in the sea via their known target strengths.

12. The system directional characteristic of a detection apparatus is in no way altered by the change of approach.

13. The ambiguity of target strength, due to pulse lengthening, is entirely eliminated by the new definitions. Equally there is no objection to making reference to the target strength of a multiple target, though of course it would still be inappropriate to allot a T value to any shoal which was not small compared with the acoustic beam at the range in question.

Finally the remarks in paragraph 15 of the original paper can be discounted as unimportant.

CONCLUSIONS

It may be an advantage to rewrite the basic text books and training manuals in terms of energy units. There is an advantage in comprehensibility, and some simplification even for experts.

Symbols not defined in text.

B = the system directional factor = $b_1 \, b_2$ where b_2 is the receiver directional factor.

INTEGRAL TRANSFORM METHOD FOR EXTRACTING TARGET STRENGTH DISTRIBUTION FROM RECEIVED ECHO SIGNALS

by
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RESUME

Une nouvelle méthode methematique est décrite, permettant de determiner le fonction de probabilité de densité ou l'histogramme de l'index de réflexion pour une population echantillonnée acoustiquement à l'aide d'un transducteur a simple faisceau. La méthode traite les echos décomposées et est elaborée directement sur un ordinateur digital.

ABSTRACT

A new mathematical technique for determining the probability density function or histogram of target strength for a population of fish acoustically sampled through a single beam transducer is described. The method processes resolved echo signals and is readily implemented on a digital computer.

1. INTRODUCTION

For several years researchers have sought methods to calculate fish target strength (i.e. scattering cross section) probability distribution from batches of recorded echo intensities. These echos are produced by individual fish passing through the detection zone of a conventional echo sounder. The greatest obstacle has been the removal of the effects transducer directivity (deconvolution) which acts as a kind of spatial filter on the target strength probability distribution. In practice it is impossible to fix the position of an isolated scatterer within the acoustic beam and hence the two-way directivity factor cannot be scaled from each resolved fish echo in a deterministic manner. Various solutions have been proposed including a special hardware configuration incorporating a dual beam system (Ehrenberg (1974)) and some statistical methods including efforts by Craig and Forbes (1969), and Robinson (1978). These attempts seem to have met with varying degrees of success and some are still under development.

The method of solution to be presented here relies on integral transform techniques for extraction of the target strength density function from recorded echo intensities. The benefit of this approach is that it avoids matrix inversion, necessary in most previous approaches, which tend to be troublesome and tedious.

2. PROBLEM STATEMENT

If an isolated scatterer (fish) is located within range of a single transducer used both for transmission and reception the acoustic intensity, I, of the received echo is given by

$$I = \frac{Ke^{-2\alpha R}}{R^4} B^2(\theta,\phi) \cdot \sigma_s \tag{1}$$

where

σ_s = scattering cross section of fish (target strength = $10 \log_{10} (\sigma_s/4\pi)$)

K = equipment scale factors, source level, etc.

α = path attenuation loss

R = range to target

$B(\theta,\phi)$ = one-way beam directivity function

(θ,ϕ) = angular coordinates relative to reference frame fixed at transducer

In practice, Eq. (1) may be scaled for the known range and equipment factors. Assume this is done for each ensonified target and let a (scaled) data set $\{z_i\}$ of N elements be gathered from the recorded echoes such that

$$z_i \equiv B^2(\theta_i,\phi_i)\,\sigma_{s_i} \quad , \quad (i=1,2,\ldots N) \tag{2}$$

This data is presumed to be sampled from a population of fish targets of random scattering cross section, σ_s. The angular coordinates (θ,ϕ) may be treated as jointly random variables statistically independent of σ_s (see for example Robinson (1978) or Lozow (1980)) and thus $B^2(\theta,\phi)$ must be regarded as a random variable itself, being a function of (θ,ϕ). The object of this analysis is to manipulate the accessible data set $\{z_i\}$ to yield the probability density function of the random scattering variable σ_s. It is immediately apparent from Eqs. (1) and or (2) that the random directivity function

$B^2(\theta,\phi)$ shrouds the desired variable (σ_s) as a random multiplier and therein lies the impediment.

For notational convenience define

$$\left.\begin{aligned} x &\equiv \sigma_s \\ y &\equiv B^2(\theta,\phi) \end{aligned}\right\} \tag{3}$$

and thus Eq. (2) becomes, for the ith data element,

$$z_i = x_i \cdot y_i \tag{4}$$

where x_i and y_i are independent random variables. A well known result from probability theory (see Papoulis p.p. 205) gives the density function of the product of two independent random variables:

If $z = xy$ and x and y are positive independent random variables then

$$P_z(z) = \int_0^\infty P_x(x)\, P_y\left(\frac{z}{x}\right) \frac{dx}{x} \tag{5}$$

where $P_x(\cdot)$, $P_y(\cdot)$ and $P_z(\cdot)$ are the marginal probability density functions of x, y and z respectively. The mathematical problem posed is:

Given the relationship Eq. (5), extract the scattering cross section probability density function denoted by $P_x(x)$ from the $P_z(z)$, of which a reasonable facsimile is presumed to be reducible from $\{z_i\}$ the data set.

3. APPROXIMATE SOLUTION OF Eq. (5) FOR $P_x(x)$

Let M be the largest value of target strength in a given population of fish. Then $P_x(x) = 0$ for $x \geqslant M$. Now define a new random variable τ such that

$$\tau \equiv \log_e\left(\frac{M}{z}\right) \tag{6}$$

where z is given by Eq. (4) (subscript i deleted). Thus τ is a random variable, since its a function of z, and it has probability density function $P_\tau(\tau)$. Assume that $P_\tau(\tau)$ may be expanded in some convenient set of orthogonal polynomials $\psi_n(\tau)$ over the interval (o,∞), such that

$$P_\tau(\tau) = \sum_{n=o}^{\infty} A_n\, \psi_n(\tau) \tag{7}$$

where the A_n are the coefficients of expansion. By definition, each $\psi_n(\tau)$ is a polynomial of highest degree n. Thus Eq. (7) may be rewritten in an ascending order of powers* of the argument τ,

$$P_\tau(\tau) = \sum_{n=o}^{\infty} A_n\, \psi_n(\tau) = \sum_{n=1}^{\infty} a_n\, \tau^n \tag{8}$$

It may then be shown (see Appendix B) that a series solution to the integral Eq. (5) for the target strength density function $P_x(x)$ is given by

$$P_x(x) = \frac{1}{2}\left(\frac{\pi D}{\lambda}\phi_m\right)^2 \frac{1}{x} \sum_{n=1}^{\infty} n a_n \left[\log_e \frac{M}{x}\right]^{n-1}$$

$$\text{for} \quad \left(Me^{-\frac{1}{2}\left(\frac{\pi D}{\lambda}\phi_m\right)^2} \leqslant x \leqslant M\right) \tag{9}$$

where:

a_n = the coefficients appearing in Eq. (8)

ϕ_m = the maximum angle ϕ (in radians) that a target may be detected

4. PROOF OF SOLUTION (Eq. 9)

For Eq. (9) to be a valid solution for the probability density function $P_x(x)$ it must satisfy Eq. (5). To see that it does, note that from Eq. (6)

$$\tau = \log_e (M/z) \tag{6}$$

or inversely,

$$z = Me^{-\tau} \tag{10}$$

From Eq. (10) it follows (see Papoulis pp. 126) that the derived density of z in terms of the random quantity τ is

$$P_z(z) = P_\tau[\tau(z)] / \left|\frac{dz}{d\tau}\right| = \frac{P_\tau[\tau(z)]}{z} \tag{11}$$

Substituting Eq. (6) into Eq. (11) and Eq. (11) into Eq. (8) results in

$$P_z(z) = \frac{1}{z} \sum_{n=1}^{\infty} a_n \left[\log_e (M/z)\right]^n \tag{12}$$

$$\left(\text{for } Me^{-\frac{1}{2}\left(\frac{\pi D}{\lambda}\phi_m\right)^2} \leqslant z \leqslant M\right)$$

which we will use to represent the left-hand side of Eq. (5).

---

*Note that $P_\tau(0)$ must be 0 (see footnote Appendix B).

SERIES EXPANSION FOR Z(s)

Recall that Z(s) is the Mellin Transform of the echo data density function $P_z(z)$. By definition

$$Z(s) = \int_0^\infty z^{s-1} P_z(z)\, dz \qquad \text{(B-11)}$$

The following transformtion of z has been found to be very useful in the eventual substitution of Eq. (B-11) into the inversion Eq. (B-10). Define a new variable τ such that

$$\tau \equiv \log_e(M/z)$$

or (B-12)

$$z = Me^{-\tau}$$

where

M = maximum value of the data z_i

Since z is a random variable it follows that τ is. Furthermore the derived probability density function of τ is

$$P_\tau(\tau) = \frac{P_z[z(\tau)]}{\left|\frac{d\tau}{dz}\right|} = Me^{-\tau} P_z(Me^{-\tau}) \qquad \text{(B-13)}$$

Substituting Eq. (B-12) and Eq. (B-13) into Eq. (B-11) yields

$$Z(s) = M^{s-1} \int_0^\infty P_\tau(\tau)\, e^{\tau}\, e^{-s\tau}\, d\tau \qquad \text{(B-14)}$$

(Note that Z(s) as given by Eq. (B-14) may be interpreted as the Laplace Transform of $P_\tau(\tau)\, e^\tau$.)

Suppose that $P_\tau(\tau)$ can be represented (see Eq. (8) in text) by a series expansion*

$$P(\tau) = \sum_{n=1}^\infty a_n \tau^n \qquad \text{(B-15)}$$

Inserting Eq. (B-15) into Eq. (B-14) yields

$$Z(s) = M^{s-1} \sum_{n=1}^\infty a_n \frac{n!}{(s-1)^{n+1}} \qquad \text{(B-16)}$$

Inserting Eq. (B-16) into Eq. (B-10) results (after some rearranging)

$$P_x(x) = \frac{1}{\epsilon^2 M} \sum_{n=1}^\infty a_n\, n!$$

$$\frac{1}{2\pi j} \int_{c-j\infty}^{c+j\infty} \frac{e^{s \log_e(M/x)}}{(s-1)^n \left(1 - e^{-(s-1)/\epsilon^2}\right)} \qquad \text{(B-17)}$$

Finally, define an auxiliary variable

$$t = \log_e(M/x) \qquad \text{(B-18)}$$

and substitute the integral term in Eq. (B-17):

$$\int_{c-j\infty}^{c+j\infty} \frac{e^{st}\, ds}{(s-1)^n(1 - e^{-(s-1)/\epsilon^2}} =$$

Inverse Laplace Transform of

$$\frac{1}{(s-1)^n(1 - e^{-(s-1)/\epsilon^2}}$$

$$= (\epsilon \to 0)\, \frac{e^t\, t^{n-1}}{(n-1)!} \quad (t > 0) \qquad \text{(B-19)}$$

Finally, using Eq. (B-18) in Eq. (B-19), and substituting the result in Eq. (B-17), yields the solution

$$P_x(x) = \frac{1}{\epsilon^2 x} \sum_{n=1}^\infty n a_n \left[\log_e \frac{M}{x}\right]^{n-1}$$

$$\text{for } \left(x > Me^{-1/\epsilon^2}\right) \qquad \text{(B-20)}$$

where

$$\epsilon = \sqrt{2}\, \frac{\lambda}{\pi D \phi_m}$$

---

*From Eq. (B-13) and Eq. (B-1):

$$P_\tau(0) = M P_z(M) = M \int_0^\infty P_x(x) P_y\left(\frac{M}{x}\right) dx = 0$$

since $P_x(x) = 0$ for $x \geqslant M$ and $P_y\left(\frac{M}{x}\right) = 0$ for $\frac{M}{x} > 1$

so (A-5) is a true density function.

A simplified density function for y may now be derived from (A-2) and (A-3) and a standard technique (outlined in Popoulis pp. 126):

$$P_y(y) = \frac{P_\phi[\phi(y)]}{|dy/d\phi|} \cong \frac{2}{\phi_m^2} \frac{\phi(y)}{2\,\frac{1}{2}\left(\frac{\pi D}{\lambda}\right)^2 \phi_m^2\, y}$$

or

$$P_y(y) \cong \frac{2}{\phi_m^2\left(\frac{\pi D}{\lambda}\right)^2} \frac{1}{y}$$

$$\text{for}\left(e^{-\frac{1}{2}\left(\frac{\pi D\phi_m}{\lambda}\right)^2} \leqslant y \leqslant 1\right) \qquad \text{(A-6)}$$

APPENDIX B: SOLUTION OF THE INTEGRAL EQUATION (5)

Given $P_z(z)$ as derived from the echo data and an analytical form for $P_y(y)$ (see Eq. A-6) it is desired to solve the integral equation

$$P_z(z) = \int_0^\infty P_x(x)\, P_y\left(\frac{z}{x}\right) \frac{dx}{x} \qquad \text{(B-1)}$$

for $P_x(x)$.

A natural mathematical tool to apply to Eq. (5) or Eq. (B-1) is the Mellin Transform (Davies 1978). The Mellin Transform is closely related to the well known Laplace Transform but has its own particular properties. The Mellin Transform of an arbitrary function f(x) is defined

$$F(s) \equiv \int_0^\infty x^{s-1} f(x)\, dx \qquad \text{(B-2)}$$

and the inverse Mellin Transform is

$$f(x) = \frac{1}{2\pi j} \int_{c-j\infty}^{c+j\infty} x^{-s} F(s)\, ds \qquad \text{(B-3)}$$

where c lies in the region of convergence of Eq. (B-2).

As defined Eq. (B-2) is the Mellin Transform of an arbitrary function f(x) and Eq. (B-3) is the Mellin inversion formula. Now the following property of this transform is of great usefulness (see Davies 1978, p. 202):

If

$$f(z) = \int_0^\infty x^n g(x/y)\, h(y)\, dy \qquad \text{(B-4)}$$

then for any n,

$$F(s) = G(s) \cdot H(n+1+s) \qquad \text{(B-5)}$$

where F(s), G(s) and H(s) are the Mellin Transforms of the functions f(•), g(•) and h(•) respectively.

Comparing Eq. (B-4) with Eq. (B-1), and identifying functions f(•), g(•) and h(•) with probability density functions $P_x(\cdot)$, $P_y(\cdot)$ and $P_z(\cdot)$ respectively it follows from Eq. (B-5) with n = -1 that

$$Z(s) = X(s)\, Y(s) \qquad \text{(B-6)}$$

where Z(s), X(s) and Y(s) are the Mellin Transforms of $P_z(z)$, $P_x(x)$ and $P_y(y)$ respectively. From Eq. (B-6)

$$X(s) = \frac{Z(s)}{Y(s)} \qquad \text{(B-7)}$$

and from Eq. (B-3)

$$P_x(x) = \frac{1}{2\pi j} \int_{c-j\infty}^{c+j\infty} x^{-s} X(s)\, ds$$

$$= \frac{1}{2\pi j} \int_{c-j\infty}^{c+j\infty} x^{-s} \frac{Z(s)}{Y(s)}\, ds \qquad \text{(B-8)}$$

Thus Eq. (B-8) implies the solution for $P_x(x)$ in terms of the Mellin Transforms of $P_z(z)$ and $P_y(y)$ respectively. The Mellin Transform of $P_y(y)$ may be found from Eq. (A-6):

$$Y(s) = \epsilon^2 \int_{e^{-1/\epsilon^2}}^{1} y^{s-1} \cdot \frac{1}{y}\, dy$$

$$= \frac{\epsilon^2\left(1 - e^{(1-s)/\epsilon^2}\right)}{s-1} \qquad \text{(B-9)}$$

(Real {s} ⩾ 1)

where

$$\epsilon \equiv \frac{\sqrt{2}\,\lambda}{\pi D\phi_m}$$

Now inserting Eq. (B-9) into Eq. (B-8) yields

$$P_x(x) = \frac{1}{2\pi j \epsilon^2} \int_{c-j\infty}^{c+j\infty} \frac{x^{-s} Z(s)(s-1)}{1 - e^{(1-s)/\epsilon^2}}\, ds$$

(B-10)

It now remains to formulate Z(s) the Mellin Transform of density function $P_z(z)$ for insertion into Eq. (B-10). A technique is described below.

Now it is shown in Appendix A that a good approximation to the probability density function of y (the random variable representing the directivity function) is

$$P_y(y) \cong \begin{cases} \dfrac{2}{y\left(\dfrac{\pi D\phi_m}{\lambda}\right)^2} & \text{for } e^{-\frac{1}{2}\left(\frac{\pi D\phi_m}{\lambda}\right)^2} < y < 1 \\ 0 & \text{elsewhere} \end{cases} \qquad (13)$$

Substituting Eq. (9) and Eq. (13) into Eq. (5) and performing the elementary integration term by term:

$$\int_0^\infty P_x(x)\,P_y\left(\frac{z}{x}\right)\frac{dx}{x}$$

$$= \frac{1}{z}\int_z^M \sum_{n=1}^\infty na_n\left[\log_e \frac{M}{x}\right]^{n-1}\frac{dx}{x}$$

$$= \frac{1}{z}\sum_{n=1}^\infty na_n \int_z^M \left[\log_e \frac{M}{x}\right]^{n-1}\frac{dx}{x} \qquad (14)$$

$$= \frac{1}{z}\sum_{n=1}^\infty a_n\left[\log_e \frac{M}{z}\right]^n$$

$$\text{for } \left(Me^{-\frac{1}{2}\left(\frac{\pi D\phi_m}{\lambda}\right)^2} \leqslant z \leqslant M\right)$$

Note that the outcome of Eq. (14) which represents the right hand side of Eq. (5) is identical to Eq. (12) which is derived form of the left hand side of Eq. (5).

It thus follows that to within the stated approximations and limits of validity Eq. (9) is a solution of Eq. (5).

APPENDIX A: DERIVATION OF $P_y(y)$

The density function ascribed to the random variable, y, represents the two-way transducer directivity function $B^2(\theta,\phi)$. For present purposes this report will confine itself to circular aperture transducers, it is shown in Lozow (1979) that a good approximation to the main lobe of a circular aperture transducer is

$$y = B^2(\phi) \cong e^{-\frac{1}{2}\left(\frac{\pi D}{\lambda}\right)^2 \sin^2\phi} \qquad (A\text{-}1)$$

where

D = effective transducer diameter

λ = wavelength

The angle ϕ in (A-1) is the angle between a given ensonified target and the main acoustic axes of the transducer. For ϕ's of interest which never exceed say 0.6 or 0.7 radians the usual small angle approximation for trigonometric function are useful and much simpler for analysis. Let $\sin\phi \cong \phi$ (in radian measure) then (A-1) may be written

$$y \cong e^{-\frac{1}{2}\left(\frac{\pi D}{\lambda}\right)^2 \phi^2} \quad (\phi \lesssim 0.7) \qquad (A\text{-}2)$$

Now for targets which are uniformly distributed throughout the detection volume it may be easily shown that the probability density function for ϕ is

$$P_\phi(\phi) = \frac{\sin\phi}{1-\cos\phi_m} \quad \text{for } (0 \leqslant \phi \leqslant \phi_m) \qquad (A\text{-}3)$$

where ϕ_m is maximum ϕ that a target may be detected. If ϕ_m is relatively small (say < 0.7 radian) the small angle approximations may be used in (A-3):

$$\sin\phi \cong \phi$$
$$\cos\phi_m \cong 1 - \frac{\phi_m^2}{2} \qquad (A\text{-}4)$$

Replacing (A-4) in (A-3) results in

$$P_\phi(\phi) \cong \frac{2\phi}{\phi_m^2} \quad \text{for} \quad (0 \leqslant \phi \leqslant \phi_m) \qquad (A\text{-}5)$$

Note that

$$\int_0^{\phi_m} P_\phi(\phi)\,d\phi = \frac{2}{\phi_m^2}\cdot\frac{\phi_m^2}{2} = 1$$

THE EFFECTIVE PARAMETERS OF THE REAL ACOUSTIC BEAM

by

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ABSTRACT

In order to measure densities of marine animal concentrations in echo surveys it is necessary to know the active volume of the acoustic beam, i.e. the volume within the detection solid angle.

The analyses of the methods and accuracies of determining the active volume have shown that errors can amount to 65% when one or more of the following factors are disregarded:

the non-uniformity of acoustic back scattering by the targets,
the substitutions of the active volume of the beam by its full volume,
approximate calculation procedures,
the diversity of the parameters of different transducers of the same type,
instrumental errors in measuring the active volume *in situ* and
the uncertainty when group targets are registered.

The errors in determining the active volume can be reduced up to 10-15 percent by taking these factors into account and by improving the equipment.

RESUME

Pour déterminer la densité des concentrations au cours des prospections échométriques, il est nécessaire de connaître le volume actif du diagramme spatial de directivité du faisceau acoustique, c'est-à-dire le volume sous le diagramme à l'intérieur de l'angle solide de détection.

Selon l'analyse des méthodes et la précision de la détermination du volume actif, l'erreur peut atteindre 65%. Les sources d'erreur sont:

la non-uniformité de la rediffusion par les cibles;
la substitution du volume actif du diagramme par le volume complet;
les calculs approximatifs;
la diversité des paramètres de différents transducteurs d'un même type;
les écarts instrumentaux lors des mesures du volume actif *in situ*, et
l'indétermination de ce dernier lors de l'enregistrement des cibles groupées.

Il est possible de réduire les erreurs de détermination du volume actif jusqu'à 10-15 pourcent en prenant en compte ces facteurs et en améliorant l'équipement.

List of symbols

λ	wave length
d	diameter of circular transducer
a, b	dimensions of rectangular transducer
Θ	insonification angle
ϕ	azimuthal angle
$G_{ant}(\Theta,\phi)$	antenna directivity function by acoustic pressure in transmission or reception
$G_{scat}(\Theta)$	averaged by azimuth back scattering by fish depending on insonification angle
$G(\Theta,\phi)$	generalized directivity function
$\Psi(\Theta)$	integral directivity function
Θ_{eff}	acoustic beam effective angle
Ω	active volume (solid angle) of beam
Ω_o	full volume (solid angle) of beam
U_{amp}	echo signal amplitude
U_{min}	threshold registration voltage
D	dynamic range of registered echo signals
s	relative systematic error
δ	relative random error

1. INTRODUCTION

As known (Yudanov, Kalikhman and Tesler, 1981), in order to determine marine animal concentrations density one should know the effective parameters of the acoustic beam, i.e. the detection solid angle and the volume within this angle.

At present this active volume is not determined but is substituted by the full volume calculated from the transducer diagram. This value is a certificate parameter for each type of the acoustic transducers. However, in principle it is possible to measure the active volume in application to actual registration conditions. Errors in determining the effective parameters of the acoustic beam are caused by the following factors:

- disregard of the non-uniformity of acoustic back scattering by insonified objects;
- substitution of the active volume by the full volume;
- approximate calculations;
- diversity of characteristics of different transducers of the same type;
- instrumental errors in measuring the active volume *in situ*;
- inadequate knowledge of effective parameters in registering group targets.

Let us try and estimate the accuracy of determining the active volume of the acoustic beam in echo surveys.

2. METHOD

Let us consider each of the above sources of error.

2.1 Disregard of the non-uniformity of acoustic back scattering by insonified objects

The dependence of fish reflectivity on the insonification angle is taken into account by the generalized integral directivity function (Yudanov and Kalikhman, 1981)

$$\Psi(\Theta) = \int_0^{2\pi}\int_{\frac{\Theta}{2}}^{\frac{\pi}{2}} G(\Theta,\phi)\sin\frac{\Theta}{2}d\frac{\Theta}{2}d\phi \qquad (1)$$

$$G(\Theta,\phi) = G^4_{ant}(\Theta,\phi)G^2_{scat}(\Theta) \qquad (2)$$

where Θ - insonification angle,
ϕ - azimuthal angle,
$G_{ant}(\Theta,\phi)$ - transducer directivity function by acoustic pressure in transmission or reception,
$G_{scat}(\Theta)$ - averaged by azimuth back scattering by fish depending on insonification angle,
$G(\Theta,\phi)$ - generalized directivity function.

At present when making practical calculations non-uniformity of back scattering is usually not taken into consideration, and allowance is only made for the directivity of the acoustic transducer. An example of the generalized and transducer integral directivity diagrams is given in Fig. 1. Full volumes are determined by the formula

$$\Omega_o = \Psi(\Theta=0) \qquad (3)$$

and are 0.030 and 0.040 respectively. Thus, in this case the error s_{scat}=+33%. The error sign is systematic which means that when the non-uniformity of back scattering is disregarded it always leads to an overestimation of the effective parameters of the acoustic beam.

2.2 Substitution of the active volume of the beam by its full volume

The error of such substitution depends on the character of registration and the echo signal's dynamic range (Kalikhman, Tesler and Yudanov, 1981; Kalikhman, 1981)

$$D = \frac{U_{amp}}{U_{min}} \qquad (4)$$

where U_{amp} - echo signals amplitude,
U_{min} - threshold registration voltage.

2.2.1 Multiple targets

The results of computer calculations in application to the registration of marine animal concentrations at depths of: 400 (Fig. 2), 200, 100 and 25 m with echo sounders EK-38 and EK-120 show that already with $D \geq 1.7$ the substitution error $\delta_{subst} \leq \pm 10\%$.

I appears from Fig. 2 that the ratio between the active volume and the full volume (Ω/Ω_o) exceeds one. This paradox is caused by the distortions of registration of concentrations by fish finding instruments.

If the value D_{min}=1.7 is considered as minimum required for carrying out a hydroacoustic survey, the value Ω_o can be used with acceptable accuracy in all cases of registering multiple targets.

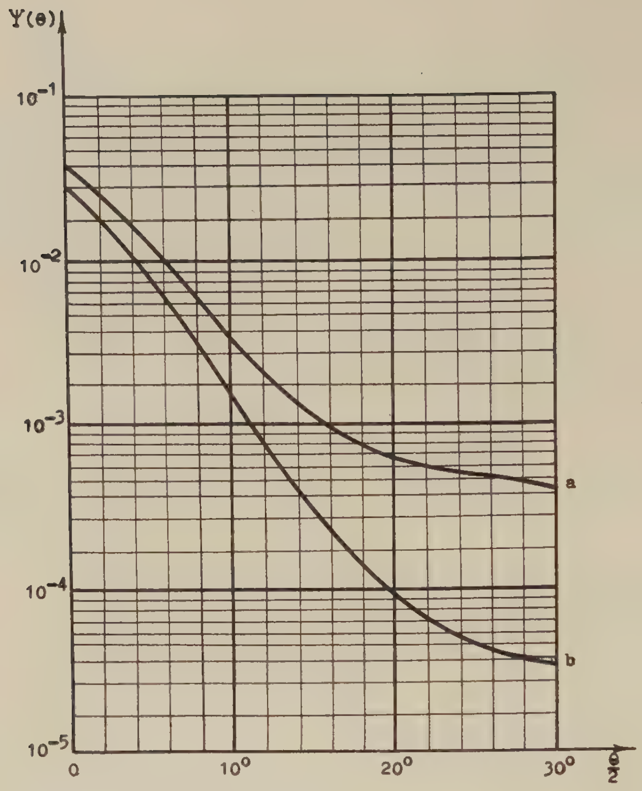

Fig. 1. Integral directivity diagrams: a- transducer type 65T of echo sounder EK-38; b- generalized for transducer 65T and back scattering by herring of 22.5 cm long.

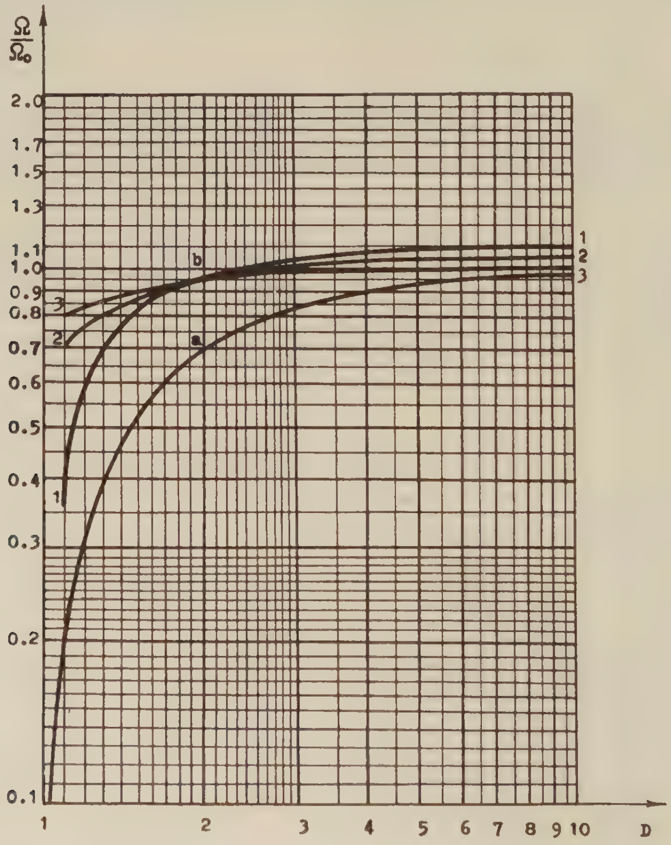

Fig. 2. Dependence of active volume/full volume ratio on echosignal's dynamic range applied to registration of: a- individual targets; b- concentration, resp. 5 m (1), 10 m (2), 25 m (3) thick, at a depth of 400 m by an echo sounder EK-38 with transducer 65T.

2.2.2 Single targets

When registering individual objects the dependences of the active volume/full volume ratio on the echo signals dynamic range are practically the same for all transducers. The generalized graph (see Fig. 1) suggests that with D≥4.0, i.e. when the single target is in the upper part of the zone of its detection by the fish-finding instrument, the substitution of the active volume by the full volume leads to an error under +10% and can be regarded as admissible. With D<4.0, i.e. when the object is registered in the lower part of the zone, the substitution of Ω by Ω_o involves great errors. In this case it is necessary to determine the active volume of the spatial directivity diagram applied to actual registration conditions, i.e. the active volume should be measured in situ.

2.3 Calculation errors

Values of Ω_o and 10 log Ω_o are calculated by a computer (Tesler, 1981) with the use of precise expressions (1) and (3) (columns 4 and 5 of Table 1). Simplified calculations of active (Ω) and full (Ω_o) volumes applied to circular or rectangular transducers can be made by the approximate formulae (Lozow, 1981)

$$\Omega_\sim = 2\pi\left(\frac{\lambda}{\pi d}\right)^2\left[1-e^{-2\left(\frac{\pi d}{\lambda}\right)^2\sin(2\cdot\theta_{eff}/4)}\right] \qquad (5)$$

or

$$\Omega_\sim = \frac{3}{2}\pi\left(\frac{\lambda}{\pi\sqrt{ab}}\right)^2\left[1-e^{-\frac{8}{3}\left(\frac{\pi\sqrt{ab}}{\lambda}\right)^2\sin(2\cdot\theta_{eff}/4)}\right] \qquad (6)$$

where λ - wave length,
d - diameter of circular antenna,
a, b - dimensions of rectangular antenna,
Θ_{eff} - acoustic beam effective angle.

When calculating by formula (5) it is necessary to observe the condition

$$x = \frac{\pi d}{\lambda}\sin\frac{\Theta_{eff}}{2} \leq 2.5 \qquad (7)$$

If $x>2.5$, the value Θ_{eff} determined from $x=2.5$ is substituted in expression (5).

When calculating Ω or Ω_o for rectangular transducers by formula (6) the effective angle averaged for longitudinal and transversal planes (or $\Theta=180^o$) is being used.

2.3.1 Full volume

The results of simplified calculations of the error:

$$\Delta = 10\ \log\Omega_o - 10\ \log\Omega_\sim \qquad (8)$$

for different transducers are shown in column 8 of Table 1 (Tesler, 1981).

The calculations for many types of wide beam ($\Omega_o>0.040$) and narrow beam ($\Omega_o<$ 0.040) transducers show mean errors of 1.9 dB and 0.3 dB respectively.

Table 1. Parameters of the acoustic beam of some Simrad echo sounders.

Parameter Type	λ cm	Transducer dimensions cm	Ω_o	$10\log\Omega_o$ dB	$\Omega_\sim$	$10\log\Omega_\sim$ dB	Δ dB	$10\log\Omega_{cer}$ dB
1	2	3	4	5	6	7	8	9
EK-12	12.5	36x46	0.06900	-11.60	0.04505	-13.40	1.80	-14
EK-18	8.33	28x50	0.02574	-15.89	0.02367	-16.26	0.37	
		28x28	0.06456	-11.90	0.04226	-13.74	1.84	-14.5
EK-38	3.95	15x30	0.01734	-17.60	0.01655	-17.80	0.20	-18
		15x10	0.07550	-11.22	0.04959	-13.04	1.82	
EK-120	1.25	d=10	0.009710	-20.13	0.009510	-20.20	0.07	
		d_{eff}= =7.3			0.01783	-17.50		-18
		d=20	0.002650	-25.70	0.002377	-26.20	0.50	
		d_{eff}= =16.25			0.00360	-24.40		-26

Thus, the calculation of the full volume boils down to calculating $10\log\Omega_\sim$ by formula (5) or (6) and adding the values of $\bar{\Delta}_w$ or $\bar{\Delta}_n$. This is equal to multiplying $\Omega_\sim$ by the coefficient 1.55 or 1.07 respectively. The maximum error of such a calculation is 0.22 dB or +5.2%, while the mean-square error is ±1.5%.

Calculations of the parameters of the beam of complex piezoceramic transducers should be made for the effective and not for the external diameters as the total area of such transducers is not equal to the operational area (columns 6 and 7).

The differences between the certificate parameters $10\log\Omega_{cer}$ (column 9) and the effective values $10\log\Omega_\sim$ indicated that the calculation of the certificate data was made by simplified formulae and should be corrected by the above method.

The effective parameters of the acoustic beam can be calculated by substituting in expression (1) not the rated but the measured directivity function (Ehrenberg, undated). The transducer under consideration in this work has the following parameters: frequency 105 kHz, width of measured diagram $\Theta_{0.7}=6^\circ$, the full volume of this diagram calculated by a computer was $\Omega_o=0.00613$.

The effective diameter of the transducer is:

$$d_{eff} = \frac{58.5\ \lambda}{\Theta_{0.7}} = \frac{58.5\times1.43}{6} = 13.9\ \text{cm} \qquad (9)$$

The result of the calculation by formula (5) and the following correction was $\Omega_o=0.00640$. The calculation error when using the simplified method is +4.4% which confirms its accuracy.

2.3.2 Active volume

The active volume of the beam can also be calculated by approximate formulae. This circumstance is accounted for by the fact that with D<4.0 the detection of individual objects is made by the central section of the main lobe which is easy to approximate by simplified expressions. Therefore the determination of the active volume by formulae (5) and (6) is accompanied by an error of less then ±5%.

2.4 Diversity of parameters of different acoustic antennae of the same type

This factor is especially significant in relation to complex piezoceramic systems and leads to errors in echo surveys when the diagram of directivity of the used transducer is unknown (Table 2).

Table 2. Parameters of eleven transducers of hydroacoustic fish-finding station Sargan (USSR).

Operation mode / Parameter		20 kHz	136 kHz	
			Wide beam	Narrow beam
Ω_o		0.0560÷0.0348	0.00443÷0.00207	0.00125÷0.000611
$\bar{\Omega}_o$		0.0427	0.00275	0.000891
$10 \log \Omega_o$, dB		-(12.5÷14.5)	-(23.5÷26.8)	-(29.0÷32.1)
$10 \log \bar{\Omega}_o$, dB		-13.7	-25.5	-30.5
Percent error when substituting Ω_o by $\bar{\Omega}_o$	Maximal	-24	-38	+46
	Mean-square	±16	±18	±28

2.5 Errors of measuring the active volume of the beam in situ

These errors were estimated by mathematical simulation. The task solution procedure was as follows:

- assignment of the parameters of the fish-finding device and of concentration of objects resolved by this device;

- calculation of the active volume of the spatial directivity diagram and of the echo signals statistic series;

- assignment of calibration errors and the variation caused by these errors in the parameters of the instrument with allowance for errors of measuring devices, hydrophones, standard spheres and diversity of transducer characteristics;

- calculation of the variations of the active volume "measured" in situ originating from the echo signals statistic series and possible deviations of the instrument parameters from the true ones;

- determination of the error of "measuring" the active volume in situ by comparing the obtained values of the active volume with the assigned value.

The results of the mathematical simulation allow the following conclusions to be made:

- the diversity of the parameters of transducers of the same type leads to approximately the same errors in determining the full and active volumes of the beams;

- the errors of the measuring devices and calibration of the fish-finding instrument cause errors in determining the active volume in situ of less than 3%.

2.6 The uncertainty of the effective parameters of the acoustic beam in registering group targets

This source of error is conditioned by imperfection of the mathematical apparatus with the help of which one can find only variations of the active volume of the beam (Yudanov, Kalikhman and Tesler, 1981).

When estimating the density in this least favourable case it is expidient to average the effective parameters of the acoustic beam applied to registration of single and multiple targets. The error which appears in this process increases with the decrease of the echo signals dynamic range (see Fig. 2). For $D_{min}=1.7$ the active volumes when registering single targets are $\Omega_{sing}=0.6\Omega_o$ and for multiple targets $\Omega_{mult}=0.9\Omega_o$. By averaging these values one obtains; $\Omega_{gr}=0.75\Omega_o$, and thus the error due to the uncertainty of the effective parameters of the beam when registering groups of objects ±25%.

However, frequently individual targets and group targets are registered together with multiple targets. The contribution to the echo integrator reading will then as a rule be much larger from the multiple targets than from the other two target categories. When such mixed concentrations occur it is therefore expidient to assume that the active volume of the beam is equal to the full volume when performing the density calculations.

3. RESULTS

The resulting error of determining the active volume of the acoustic beam can be found by the addition of partial errors by the formula

$$s+\delta = \Sigma s_i + \sqrt{\Sigma \delta_j^2} \qquad (10)$$

The composition of partial errors and consequently the value of the resulting error depends on reception conditions and the type of echo signals.

3.1 D≧4.0 irrespective of the character of registration, 1.7≦D<4.0 and registering multiple targets

The sources and likely sizes of the errors of calculating the active volume are:

- the negligence of the non-uniformity of acoustic back scattering, (s_{scat}=+33%);

- the diversity of parameters of different transducers of the same type, (δ_{div}=±16%);

- the substitution of the active volume of the spatial directivity diagram by its full volume, (δ_{subst}=±10%);

- approximate calculations, (δ_{appr}=±1.5%).

As a result $s+\delta$ = (33±19)%, the error ranging from +15 to +50 percent.

3.2 1.7≦D<4.0 and registering single targets

The sources and likely sizes of the errors of measuring the active volume *in situ* are:

- the negligence of the non-uniformity of acoustic back scattering, (s_{scat}=+33%);

- the instrumental errors (δ_{div}=±16% and δ_{inst}=±3%);

- approximate calculations (δ_{appr}=±5%).

As a result $s+\delta$ = (33±17)%, the error ranging from +15 to +50 percent.

3.3 $1.7 \leq D < 4.0$ and registering group targets

The sources and likely sizes of the errors of determining the active volume are:

- the negligence of the non-uniformity of acoustic back scattering, (s_{scat}=+33%);
- the uncertainty of the effective parameters of the beam (δ_{gr}=±25%);
- the instrumental errors (δ_{div}=±16% and δ_{inst}=±3%);
- approximate calculations (δ_{appr}=±5%).

As a result $s+\delta$ = (33±30)%, the error ranging from +3 to +65 percent.

4. CONCLUSION

The analysis shows that in order to reduce the errors of determining the effective parameters of the acoustic beam the following points should be considered:

- investigating the sound back scattering properties of marine animals in different behaviour conditions and taking it into account during echo surveys;
- using measured diagrams of directivity of each transducer in the calculations;
- increasing the acoustic power and lowering the noise;
- raising the requirement of precision to the equipment.

The obtained results show that if all the above steps are considered the error of determining the effective parameters of the acoustic beam in echo surveys might be reduced to 10-15 percent.

THE DESIGN, CONSTRUCTION AND TESTING OF A MULTI-BEAM TRANSDUCER FOR IN SITU TARGET STRENGTH MEASUREMENT

by

E.J. Simmonds(1), S.T. Forbes(1) and P.J. Stevens(2)

ABSTRACT

Both dual beam and single beam techniques for in situ target strength measurement of fish depend largely on the detailed beam patterns of the transducers used. A multi-element transducer, comprising some 127 elements arranged in concentric rings to which different shading functions can be applied, has been produced to allow practical investigation of the effect of different beam patterns. The paper describes the design objectives and construction of the transducer, and the problems involved in matching to long lengths of cable. The electronics required to apply different shading functions on transmission and reception so that the transducer can be used in a dual beam mode are also described. Measurements of beam patterns for several different shading functions have been carried out, and the results of these measurements are presented.

RESUME

Les techniques acoustiques à faisceau simple ou à faisceau double pour la détermination in situ de l'index de réflexion des poissons, sont basées sur la connaissance de la directivité des transducteurs. Pour étudier les différentes caractéristiques des faisceaux, nous avons fait construire un transducteur spécial. Celui-ci comprend 127 éléments céramiques rangés en une série d'anneaux concentriques, auxquels s'appliquent des fonctions différentes de "nuance", c'est-à-dire des fonctions décrivant l'amplitude du signal appliqué à chaque anneau, ce qui nous permet de varier la forme de la fonction décrivant l'amplitude du signal appliqué a chaque anneau, et ce que nous permet aussi de varier la forme de la fonction de directivité.

L'objectif et les détails de construction de ce transducteur sont décrits ainsi que la méthode de son appariement à un câble long. Le changement de la fonction de "nuance" entre transmission et réception est donné, ce qui permet au transducteur de fonctionner à faisceau double. La directivité a été mesurée directement en utilisant des diverses fonctions de "nuance", et nous en présentons les résultats.

1. INTRODUCTION

A system was required for in situ target strength measurements at sea, and it was decided to use the dual beam technique suggested by Ehrenberg (1977). This uses a transducer to provide a single narrow beam for transmission and the same narrow beam for reception along with a co-axial wide beam. For such a system the outputs are:

$$E_W \propto B_N(\theta,\phi)B_W(\theta,\phi)\ TS$$

$$E_N \propto B_N^2(\theta,\phi)\ TS \text{ (assuming transmit and receive beam patterns are the same)}$$

where

E_W is received intensity on wide beam

E_N is received intensity on narrow beam

$B_W(\theta,\phi)$ sensitivity at angle θ,ϕ in wide beam

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$B_N(\theta,\phi)$ sensitivity at angle θ,ϕ in narrow beam

TS is the target strength of the target at angle θ,ϕ

From this: $E_w^{\;2}/E_N = B_w^{\;2}(\theta,\phi)$ TS

From the centre of the wide beam $B_W^{\;2}$ will be constant and $E_W^{\;2}$/EN is a measure of target strength. A minimum value of E_N/E_W can be selected to provide a threshold excluding signals from large angles where the above relationship does not hold.

One of the problems with a system using a conventional uniformly transducer is the high side-lobe level of both the transmit beam and the wide-angle receive beam. It was thought that by "shading" the transducer (driving it in non-uniform manner) the side-lobe level could be reduced. This process also increases the width of the main lobe and it was expected that there would be a compromise between reduction in side-lobe level and increase in transmit beam width. A transducer was constructed with a central section and five concentric rings of elements with these requirements in mind. This paper describes the transducer constructions, the shading functions and their implementation.

2. MATERIALS AND METHODS

2.1 Shading Functions for the Narrow Beam

A series of different shading functions were calculated and a range of these selected to provide steady reduction in side-lobe level. They are:

(a) Uniform (unshaded)

(b) Tchebyscheff with -30dB side-lobes (Dolf, 1946)

(c) Cosine ($\pi/2$) (θ^o to $\pi/2$ at the edge of the transducer)

(d) Linear

(e) Tchebyscheff with -40dB side-lobes

(f) Tchebyscheff with -50dB side-lobes

(g) Cosine (π)($\cos(0^o)$ + 1 to $\cos(\pi)$ + 1 at the edge of the transducer)

(h) Binomial series with three least significant terms omitted.

The calculated values for shading are given in Table 1.

Table 1. Voltage shading referred to unity at the centre of the tranducer.

Shading Function	Transducer Section					
	Centre	Ring:1	:2	:3	:4	:5
a) Uniform	1	1	1	1	1	1
b) Cheb - 30dB	1	1.18	0.97	0.73	0.49	0.37
c) Cosein ($\pi/2$)	1	0.91	0.80	0.64	0.44	0.23
d) Linear	1	0.833	0.667	0.5	0.333	0.166
e) Cheb - 40dB	1	1.12	0.86	0.57	0.32	0.16
f) Cheb - 50dB	1	1.07	0.76	0.46	0.22	0.08
g) Cosine (π)	1	0.84	0.63	0.40	0.20	0.05
h) Binomial	1	0.80	0.52	0.26	0.10	0.03

Computer calculations of expected beam patterns for CW were carried out assuming that the transducer was a 127 element array of pistol elements. The results of three

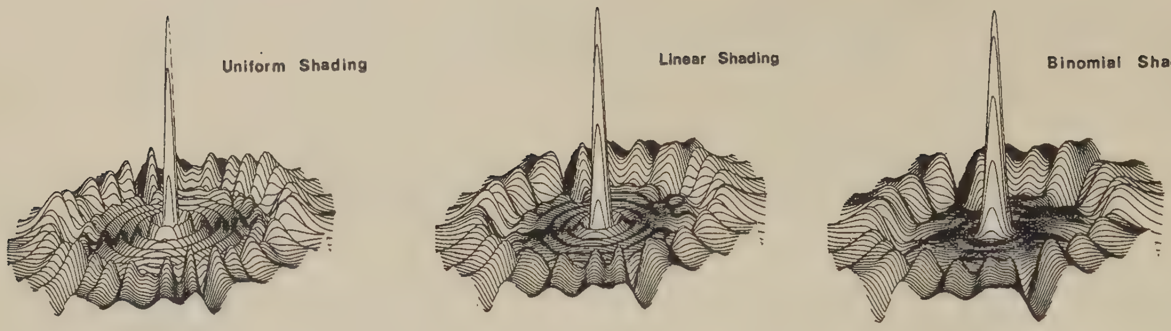

Fig. 1. Pictorial representation of 3 types of shading showing the normal unshaded pattern the extreme Binomial and the linear pattern used in practice.

of these are shown in a pictorial form in Fig. 1. They cover the range of patterns and show the increase in the width of the main lobe as the side-lobes are reduced. The outer side lobes which are at angles of 70° or more are not affected by the shading because these are due to the array spacing.

The wide beam for reception is obtained by using the central part of the transducer on its own.

In order to determine the best shading function and correct the signal processing that would be required a test system was constructed from several discrete parts.

(1) Transducer
(2) Transmitter
(3) Receiver Beam Formers
(4) Variable Gain Amplifiers
(5) Bandpass Filters
(6) Envelope Detectors
(7) Computer Processing

In addition to this a computer controlled motorised gimbal table was used to carry out automated measurements at different angles. The complete system can be seen as a block diagram in Fig. 2.

2.2 Transducer

The transducer is constructed from 127 elements arranged in five concentric rings around a central cluster (Fig. 3(b)).

The individual transducer elements (Fig. 3(a)) are of the pre-stressed sandwich resonator type containing two 30 mm diameter PZT4 ceramic rings, 5 mm thich. The radiating head material is aluminium and the tail mass is steel. Each element is mounted on a pad of polyurethane foam, has a compressive strength of 750 psi. The radiating faces are encapsulated with polyurethane and the case is machined from a solid cast block of Nylatron GSM.

Each ring of elements is separately wired to a socket to allow external beam forming.

2.3 Transducer matching

Each ring of elements was tuned with a transformer so that the impedance at 38 kHz was real and matched the characteristic impedance of the connecting cable. Because the impedance of the transducer has both real and imaginary components, it cannot be perfectly matched to a normal cable at all frequencies. The cable rotates this complex impedance and a complete rotation occurs each half wave length. This means that cables of multiples of 1/4 wavelength are relatively easy to drive but complicated matching is required for intermediate lengths (Stevens, 1980). The cable used for this work has

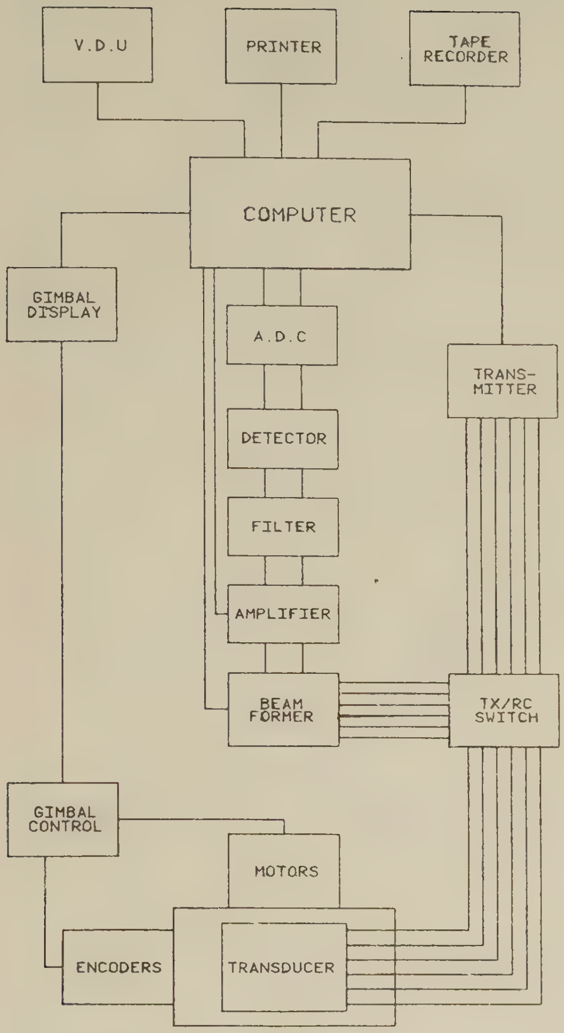

Fig. 2. System block diagram.

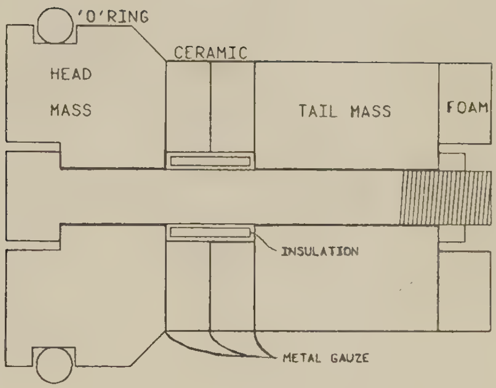

Fig. 3a. Cross-section of transducer element

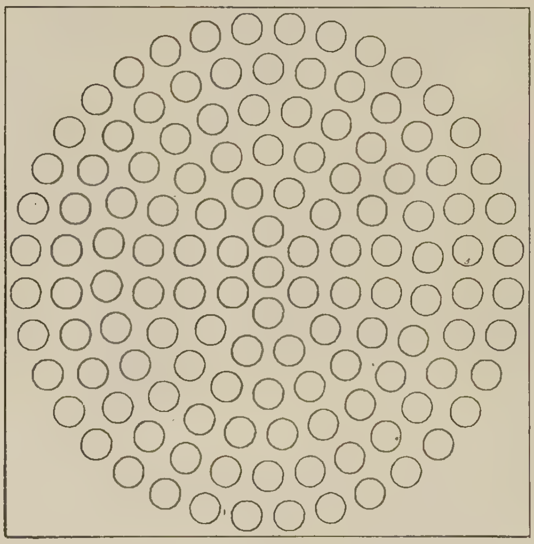

Fig. 3. Transducer and element construction.

a length of 1100 m or 0.23 wavelengths and this is sufficiently close to 0.25 wavelengths. However, because the cable is a 1/4 wavelength the impedance of the transducer is transformed from a series to parallel tuned circuit. For this reason voltage drive transmitters are required rather than current drive which is suitable for series tuned systems.

2.4 Transmitter

A Loughborough University designed transmitter (Pratt, 1979) was slightly modified so that it could be used to drive six separate amplitude controlled channels. The control circuit and the transmitter output stage are shown in Fig. 4 for a single channel. In normal use the output stages were designed to be connected together to provide increased power. For this system the output transformers were rewound so that the modules could work independently and six of these were operated synchronously. The output levels could not be predicted so each level was set individually by adjusting the output with the trim potentionmeters shown in Fig. 4 while measuring the voltage on the terminals of the transducer. Any set of preset transmitter outputs could be computer selected.

2.5 Beam Former (Fig. 5)

This is a summing point amplifier which provides different gains for each input. The gains are selected using the computer controlled multiplexers. The input transformer insolates the cable, and the parallel input resistor is equal to the characte-

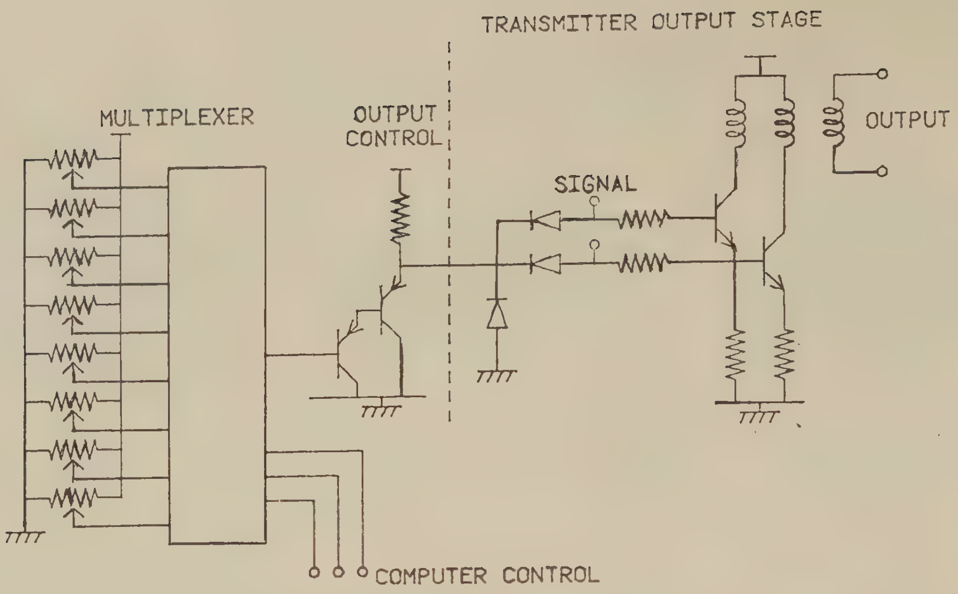

Fig. 4. Transmitter control circuit (one channel).

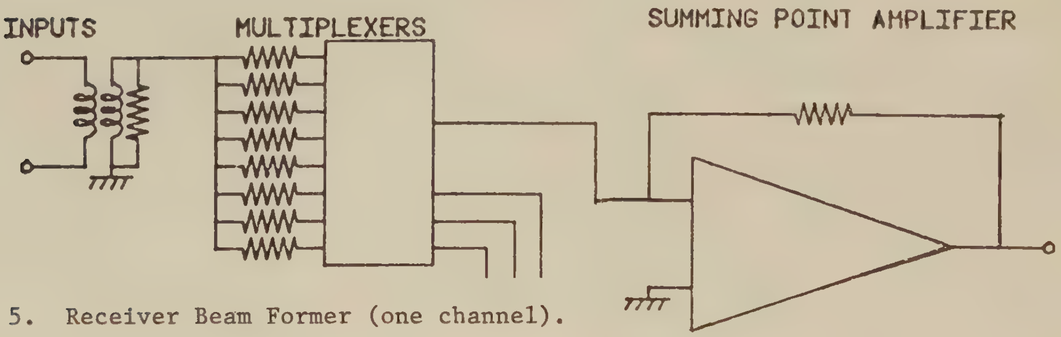

Fig. 5. Receiver Beam Former (one channel).

ristic impedance of the cable. Two of these summing point amplifier and multiplexer combinations were used so that two receiver beams could be formed simultaneously.

2.6 Variable gain amplifier (Fig. 6)

A simple method providing a digital controlled 6dB steeped gain amplifier uses a DAC in the feedback loop of an operational amplifier. This did not produce particularly accurate gain steps, but they were stable. The gain of each setting was measured and recorded and these values were used to correct for errors.

2.7 Filter (Fig. 7)

A bandpass filter is required to reduce unwanted noise. For optimum signal to noise ratio a filter with rectangular frequency response would be required.

One good approximation to this is a Tchebyscheff filter. This design was tried but rejected because this steep sided filter produces significant ringing on the received pulse. The system is required to resolve single pulses and for this the received echoes must have both rapid rise times and flat tops with minimum bandwidth. Maximum linear phase filters (sometimes, called Bessel Filters) provide a response of this type.

A three pole bandpass design (STC 1956) with 5 kHz -3dB bandwith was used. The frequency response can be seen in Fig. 9(d). The pulse performance can be seen by comparing Fig. 9(a) which shows an input of 0.5 ms pulse, modified by 6 kHz bandwidth to take account of the transducer, with Fig. 9(b) which shows the same pulse half wave rectified after passing through the filter.

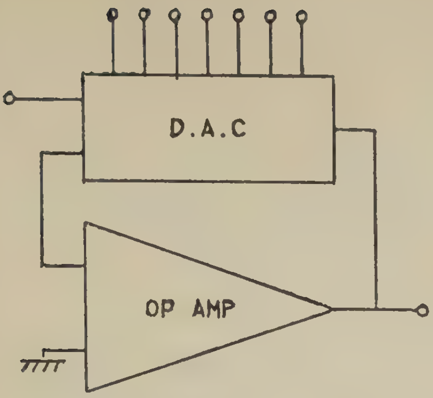

Fig. 6. Digital controlled gain stage.

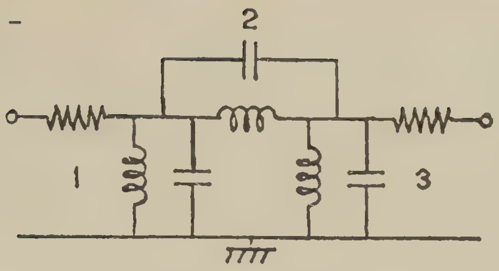

Fig. 7. Three pole Band Pass Filter (Bessel design)

L_1 = 135mH R_1 = 500 C_1 = 130pF

L_2 = .816mH C_2 = .0215 μF

L_3 = .119mH R_r = 500 C_3 = .147 μF

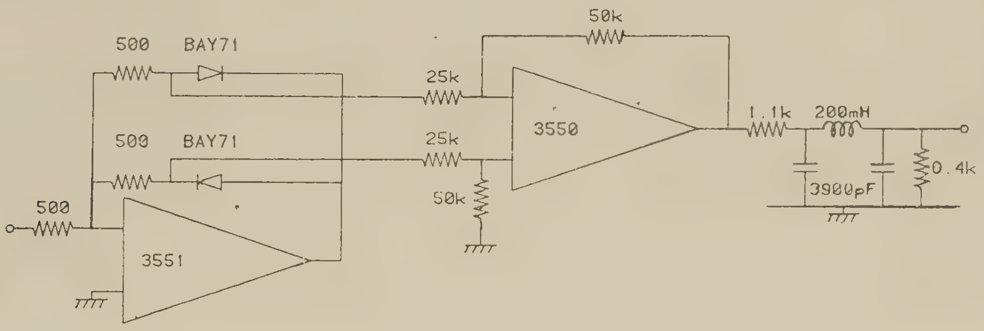

Fig. 8. Detector.

The result is an output which has a rise time of 0.15 ms and for a 0.5 ms pulse provides 250 μs of flat top for measurement purposes.

2.8 The Detector

This is fairly conventional design using a fast slow rate operational amplifier to produce the two half wave rectified signals and a differential amplifier to sum them. The full wave rectified signal can be seen in Fig. 9(b), this is then smoothed using a 'constant K' 4 kHz bandwidth base band filter. The bandwidth is chosen to be as wide as possible while keeping the ripple to less than 1 mV. The choice of components for the rectifier stage is quite critical and 0.5% resistors and fast diodes are required for this detector to give 55 dB of dynamic range with +0.1 dB linearity.

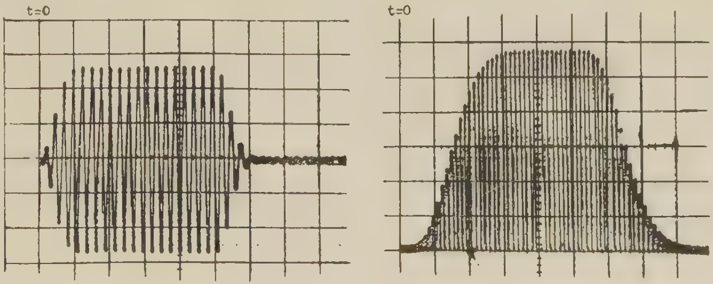

Fig. 9a. 0.1ms/div
INPUT PULSE

Fig. 9b. 0.1ms/div
RECTIFIED FILTERED PULSE

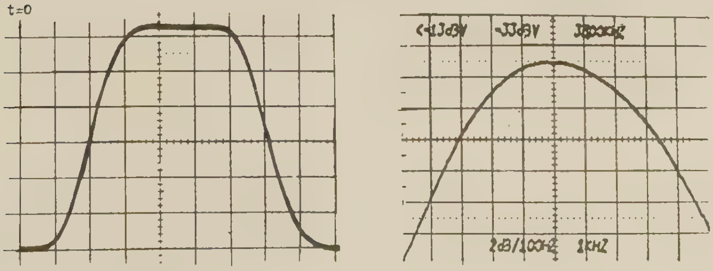

Fig. 9c. 0.1ms/div
RECTIFIED FILTERED AND
SMOOTHED PULSE

Fig. 9d. CENTRE FREQUENCY 38kHz
1kHz/div 2dB/div
FREQUENCY RESPONSE OF
BAND PASS FILTER

Fig. 9. Osciloscope traces showing an input pulse of 0.5 ms modified by 6 kHz bandwidth (9a). The same pulse filtered and detected (9b) and smoothed (9c). The frequency response of the Bessel filter (9d).

2.9 Simple and Hold and ADC

A 12 bit successive approximation ADC provides sample time of 30 μs which gives up to 16 samples per pulse length if used at full capacity.

2.10 Computer

A Computer Automation LCI 4/90 computer was used to control the system. Computer sub-routines were written to work with BASIC. This allowed flexible control of gain, beam shape, transmitter and the gimbal table was well as analysis of data during the measurements.

3. MEASUREMENTS

Measurements were carried out to verify the beam patterns and to determine which shading pattern would be most useful. A full report of these measurements is given by Forbes (1982) at this conference, only a few results are included here. All the measurements were carried out by integrating the received echo energy from a steel ball suspended beneath the transducer.

From the range of shading functions tried, linear shading for the narrow beam, was selected because this showed the best overall performance, when combined with the central element cluster as the wide beam.

Fig. 10 shows a comparison of measured and predicted beam patterns for uniform and linear shading. Figs 10(a) and (c) show two way intensity patterns for the narrow beams. Figs 10(b) and (d) show the two way intensity patterns for transmission with the narrow beam and reception on wide beam. The side-lobes are not reduced by as much as theory would suggest but there is a significant improvement of about 8 dB. This is particularly important for reception on wide beam. In all cases the measured beams are wider than predicted. The higher levels of side-lobe and smoothing of zeroes found in practice are due largely to the fact that the theoretical values are calculated for CW and do not take into account the pulse length.

Fig. 11(a) shows a plot of target strength (E_w/E_N) against the threshold (E_N/E_w) for a single target at different angles and Fig. 11(b) shows the same data plotted against angle. Fig. 11(a) indicates that the system can evaluate target strength over a 3dB change in E_N/E_w and it can be seen from Fig. 11(b) that this corresponds to a useful beam width of 6°.

4. THE MODIFIED SYSTEM FOR USE AT SEA

In order to use this system at sea the cabling requirements had to be reduced. The transmitter and receiver were reduced to two channels, and the shading was applied on both transmit and receive by resistor networks. The filter detector and ADC used for the tests are unchanged. The receiver and shading are shown in Fig. 2. The transmitter uses two channels. The high power part used to drive the outside five rings is constructed from four modules, and the low power part for the centre is a single module controlled in the manner described above.

The shading is the same for both transmit and receive. A constant impedance network is used where:

$$R_p = SZ_e/(1-S)$$

$$R_S = Z_e\ (1-S)$$

where R_S is the resistor in series with the transducer elements, R_p is in parallel. Z_e is the impedance of the ring and S is the voltage shading required. If the transducer is tuned to the transmitter frequency and used over a limited bandwidth Z_e can be regarded as a pure resistance.

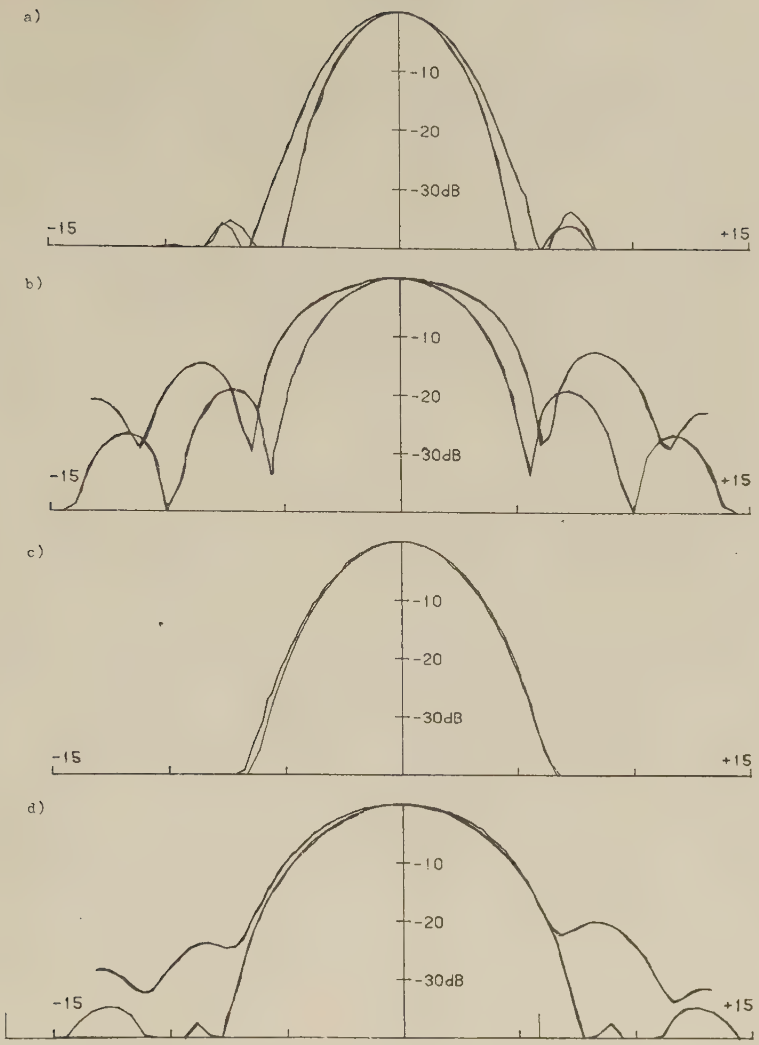

Fig. 10. Theoretical and measured beam patterns over ±15° from the acoustic axes (The theoretical patterns are narrower than the measured ones).

10a Uniform shading narrow transmit and receive
10b Uniform shading narrow transmit, wide receive
10c Linear shading narrow transmit and receive
10d Linear shading narrow transmit, wide receive.

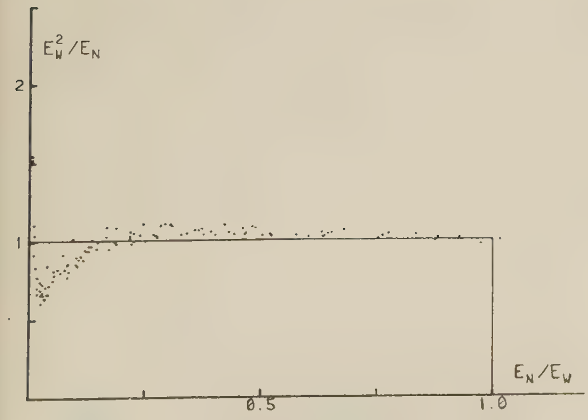

Fig. 11a. Target Strength against threshold.

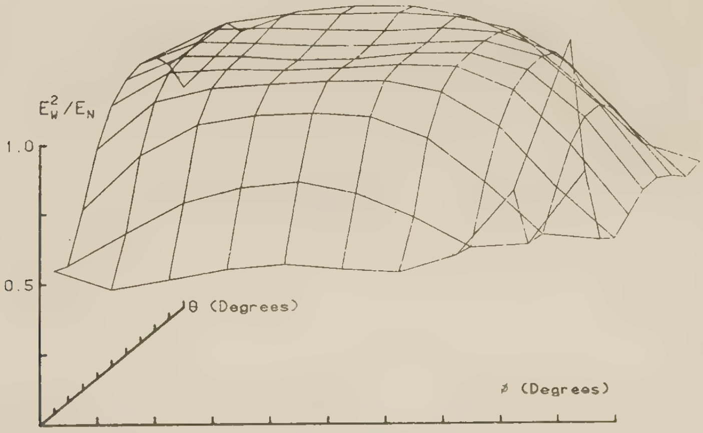

Fig. 11b. Target strength against angle from the acoustic axis 1.0° grid.

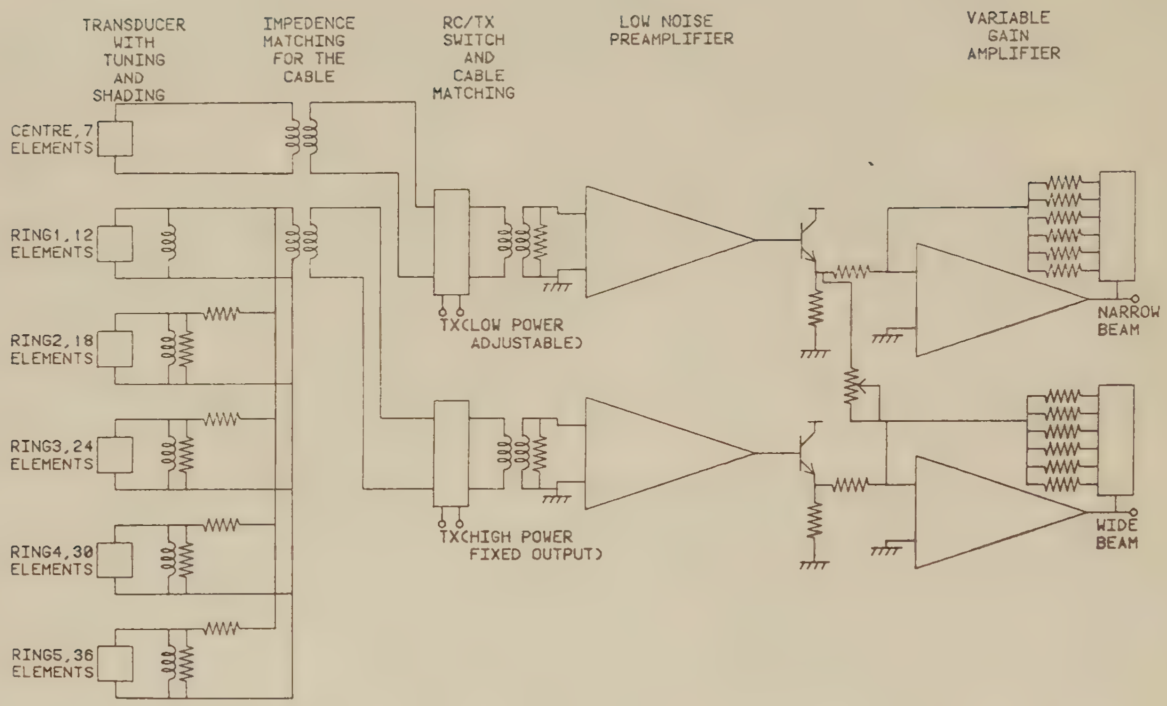

Fig. 12. Two channel receiver with transducer cable matching and shading.

The two channel reciever combines the central elements of the transducer with the outer part to produce the narrow beam and uses the central part alone to give the wide beam.

ACKNOWLEDGEMENTS

The authors would like to thank Mr P.J. Copland and Mr I.B. Petrie for their help with the electronic construction and assistance with the experimental work.

ACOUSTIC DETECTION AND ESTIMATION OF FISH NEAR THE SEA-BED AND SURFACE

by

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ABSTRACT

Certain species of pelagic fish exhibit a pattern of behaviour which causes them to spend much of the day close to the seabed and a significant part of the night near the sea surface.

These boundaries show a variability through wind induced motion at the surface and small-scale depth contour changes and roughness of the seabed which can limit the overall efficiency of biomass estimation by acoustic methods. Interaction of these factors with the parameters of the echo-sounder and the fish target strength cause uncertainties as to the zones where fish detection and echo measurement are possible.

The influence of the acoustic beam geometry and the length of the transmitted pulse on the sampled volume close to the sea bed boundary is examined. Proportions of volume sampled to volume obscured near this boundary are also considered for practical configurations of acoustic equipment. Effects of the minimum height of detection and the height anomaly near the sea bed, in relation to trawl sampling for the identification and sizing of species is discussed.

RESUME

Le comportement de certaines espèces de poissons pélagiques les amène à passer une grande partie de la journée près du fond de la mer et une portion significative de la nuit à proximité de la surface.

Les limites de ces zones présentent des variations en raison du mouvement provoqué par le vent à la surface, des changements de contour à petite échelle et des inégalités du fond de la mer, qui peuvent limiter l'efficacité globale de l'estimation de la biomasse par des méthodes acoustiques. L'interaction de ces facteurs avec les paramètres du sonar et la force de la cible - en l'occurrence le poisson - provoquent des incertitudes quant aux zones dans lesquelles la détection du poisson et la mesure de l'écho sont possibles.

L'influence de la géométrie du faisceau acoustique et de la longueur de l'impulsion transmise sur le volume échantillonné près de la limite du fond de la mer, sont examinées. Les proportions du volume echantillonné par rapport au volume obscurci près de cette limite, sont aussi prises en considération pour des configurations pratiques de matériel acoustique. Les effets de la hauteur minimale de détection et de l'anomalie de hauteur près du fond de la mer, en rapport avec l'échantillonnage au chalut pour l'identification et la détermination de la taille des espèces, sont discutés.

1. INTRODUCTION

Acoustic surveys of fish populations include both pelagic and demersal species, but it is evident that some fish in each class interchange these roles at certain times. Herring (Clupea harengus) for example spend a proportion of their lives close to the sea bed while plaice (Pleuronectes platessa L.) swim in midwater for long periods. These variations in behaviour are of some significance to the assessment of fish populations by acoustic methods since, when very near the sea surface or to the sea bed, fish may not be accessible to acoustic detection or estimation systems. In this respect two of the physical parameters of acoustic systems are important. First, the length of transmitted pulse $c\tau$, (where c is the speed of acoustic wave propagation and τ is the time duration of the pulse) which determines how close to the sea boundaries the system is effective and second, the geometry of the beam, which controls the volume sampled per transmission. Beam geometry is also responsible for errors that occur in measuring the depth of many fish away from the axis of the beam and also, the distance of fish from the sea bed or, sea surface.

This paper examines detection height relative to the sea bed, the minimum height on the beam axis, and also the effect of changes in sampled volume near the sea bed and sea surface. Rough surface and seabed conditions in relation to acoustic estimation are considered, in addition to the effect of sloping sea beds.

2. DETECTION HEIGHT ABOVE THE SEA BED

2.1 Geometrical Factors

For simplicity, a conical beam is considered, with its axis perpendicular to a flat sea bed. Beyond the fresnel zone, the wavefront of the acoustic pulse is spherical and objects on its surface will be insonified instantaneously, thereby causing their echoes to arrive simultaneously at the receiver. These echoes, although displayed at the same depth, may emanate from fish at different depths because of the spherical surface of the wavefront. For quantitative measurements this makes little difference to the results until the acoustic pulse is about to interact with the sea bed. Interaction of the pulse with the sea bed only ceases when the outer edges of the rear surface of the pulse have produced an echo.

The minimum height h, at which fish can be detected above the sea bed in relation to the spherical surface of the pulse may be calculated from

$$[h = d \;\; 1 - \cos\theta/2] + c\tau/2 \qquad (1)$$

where h = height in metres
d = total depth of water from the transducer face to the sea bed
θ = transducer full beam angle at 1/2 power points
$c\tau/2$ = half the pulse length
c = speed of acoustic wave propagation (m/s)
τ = duration of pulse in seconds.

This can be illustrated by considering a small object 'a', on the axis of the beam, placed at a height of $c\tau/2$ above the sea bed and insonified by a pulse of length ($c\tau$). When the wavefront reaches object 'a' an echo starts to return and continues until the rear surface of the pulse leaves 'a'. Meanwhile, the pulse wavefront has continued and when the axis of the beam reaches the sea bed, and echo starts to return. This echo reaches 'a', at height $c\tau/2$, at the same time as the rear surface of the pulse is leaving 'a' and hence as the rear of the echo from 'a' is returning. If 'a' were at a slightly greater height above the sea bed there would be no risk of the echoes merging.

Therefore half the pulse length $c\tau/2$, is the minimum possible height at which any object can be distinguished from the sea bed echo. An illustration is given in Fig. 1. In practise, pulses are not perfect because the overall bandwidth of the system is limited. This causes slow build-up and decay of both pulses and echoes so that $c\tau/1.5$ is often a more realistic figure.

The acoustic sampling of fish on the axis of the beam, nominally stops at a minimum height of $c\tau/2$ above the sea bed, but at angles off the axis it will stop significantly higher. This is the reason why it is rarely possible to compare quantities of fish caught in a bottom trawl to acoustic estimates made during the trawl haul.

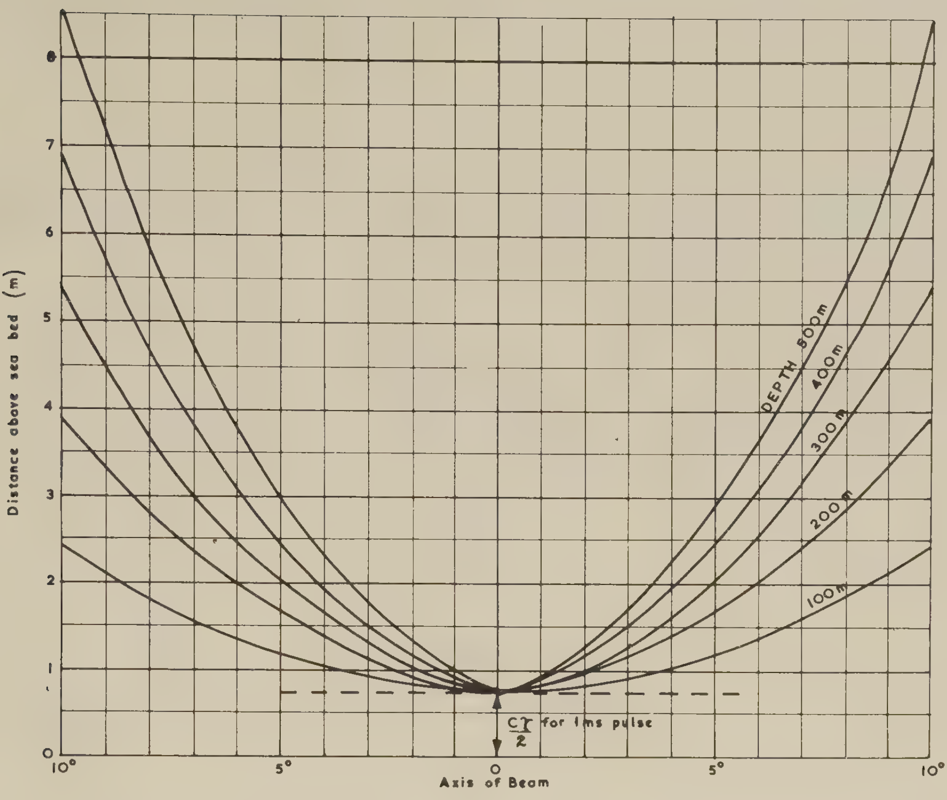

Fig. 1. Detection height above the sea bed for full beam angle θ to 20° and depths 100-500 m.

3. DETECTION VOLUME NEAR THE SEA BED

Whilst the transmitted pulse contained in a conical beam is travelling through the sea, clear of any boundaries, its volume is contained within a spherical shell of common solid angle between the ranges R_2 to R_1 where R_1-R_2 is equal to the pulse length cτ. This volume may be calculated from

$$V = (2\pi/3)(1 - \cos\theta/2)(R_1^3 - R_2^3) \qquad (2)$$

where V = the volume of the range shell in m^3
R_1 = depth of water from transducer to the pulse wavefront (m)
R_2 = " " " " " " " rear of the pulse (m)
$\theta/2$ = half angle to half power level of the beam in degrees.

At the point where the wavefront is one pulse length above the sea bed, the volume in which detection/sampling can take place is reduced to

$$V = (\pi/3)(1 - \cos\theta/2)(R_1^3 - R_2^3) \qquad (3)$$

where the units have the same dimensions as before.

As the wavefront travels through the last half pulse length to reach the distance $c\pi/2$ above the sea bed, the volume sampled diminishes to the cap of a sphere which itself finally reduces to zero at the wavefront height or $c\pi/2$. For the situation outlined, the cap is on the axis of the beam and the minimum useful sampling volume will occur when the dorsiventral height of a fish is slightly less than the height of arc associated with the cap.

Volume of cap of sphere in m^3

$$V = (\pi h_1{}^2/3)(3R_1 - h_1) \qquad (4)$$

where h_1 = height of the arc (m)

However, this volume is likely to be insignificant compared to the rest of the volume sampled by the acoustic beam. Having established the limit to sampling near the sea bed, and the reduction in volume sampled as the limit is approached, it is possible to examine the zone where there can be no detection.

4. VOLUME OF DEAD ZONE

The near-seabed, dead zone can be divided into two regions, one, where there is no possibility of sampling by acoustic means, i.e. within the distance of $c\tau/2$ above the sea bed. Then there is a zone immediately above this distance, which may be partially sampled as the vessel moves along its track and successive transmissions overlap. Fig. 2 (a) and (b) illustrates these zones. First, consider the total dead zone volume.

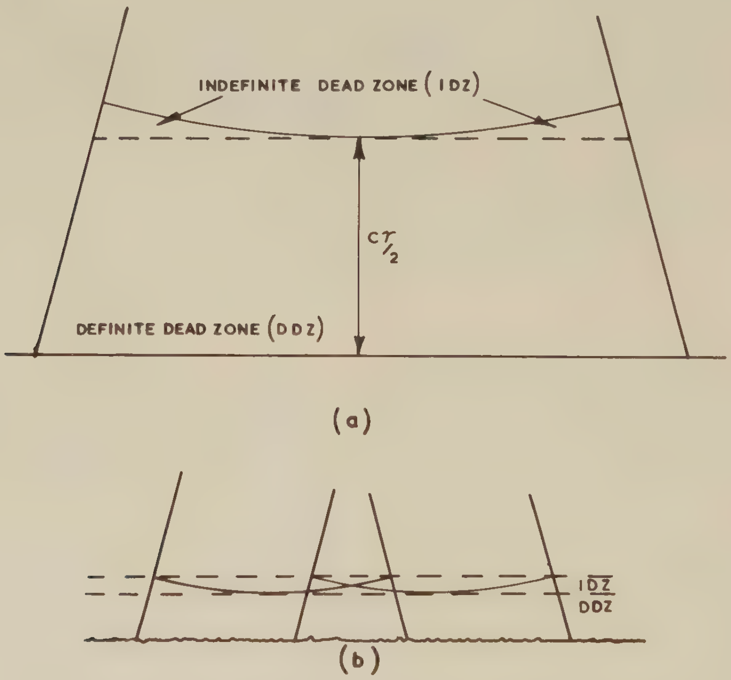

Fig. 2. Showing how the 'dead' zone may be divided into two regions.

This volume, when related to a conical beam, comprises the frustrum of a cone minus the cap of a sphere. In terms of the depth of water from transducer to sea bed (d), the beam angle θ and the pulse length $c\tau$ it can be expressed as

Volume of dead zone = Volume of frustrum - Volume of cap

$$V_{frustrum} = 0.268\ (d - c\tau/2)(1 \underset{2}{-} \sin\theta/2/\tan\theta/2) + c\tau/2\ [(2\ d \tan\theta/2)]^2 + 2(d - c\tau/2)\ \sin\theta/2)^2 + (2\ d \tan\theta/2)(2\,[\,d - c\tau/2\,]\sin\theta/2) \qquad (5)$$

$$V_{cap} = \pi/3\ [(d - c\tau/2)(1-\sin\theta/2/\tan\theta/2)]^2\ [3(d - c\tau/2)-(d-c\tau/2)(1-\sin\theta/2/\tan\theta/2)] \qquad (6)$$

Fig. 3 has been plotted using practical values of beam angles and pulse durations in equations 5 and 6. From this figure it is evident that beam angle is the most significant factor in determining the volume of the dead zone, therefore the rate of increase of this zone with depth is considerable, see Fig. 4.

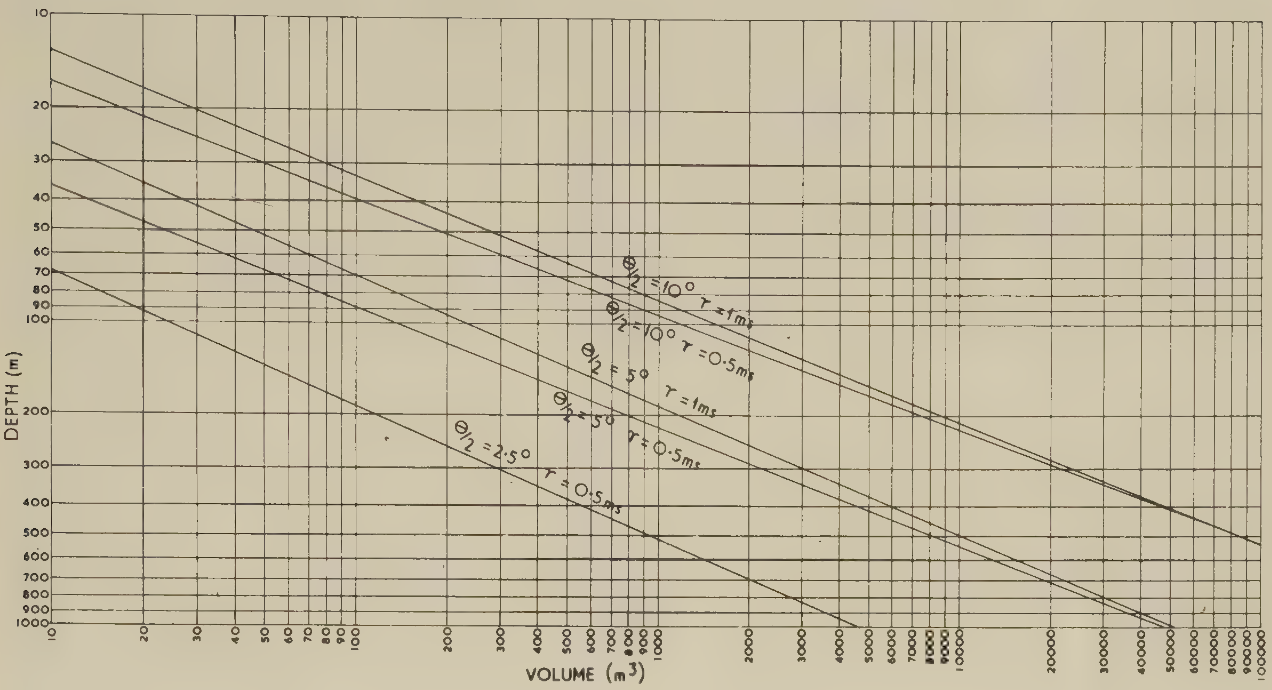

Fig. 3. Volume of dead zone for different beam angles and pulse duration.

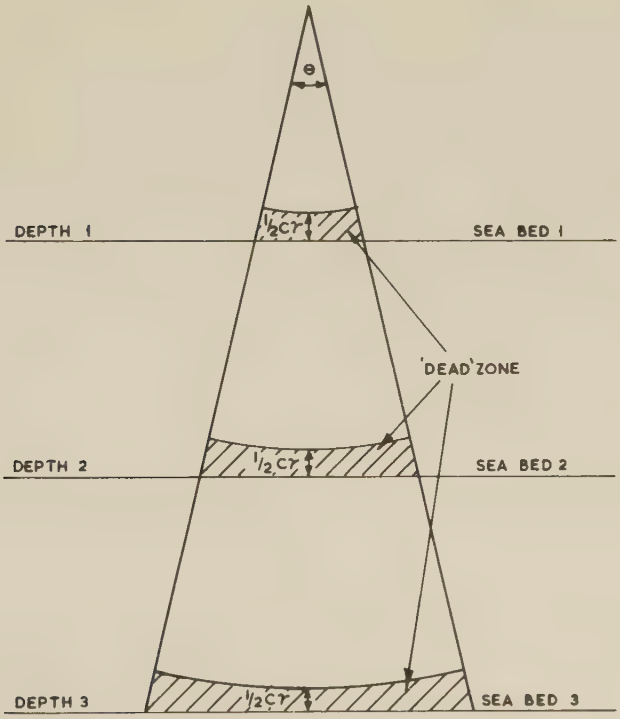

Fig. 4. Section through the centre of a beam to illustrate the increase in volume of the 'dead' zone as depth increases.

The volume given above for the dead zone relates to one transmission only, whereas a succession of transmissions occur as the vessel moves along its course. Depending on the beam angle, the speed of the vessel and the depth of water, these transmissions may overlap, especially near the sea bed. Thus some variability occurs in the effective sampled volume of the region where the pulse approaches the height above sea bed of $c\tau/2$. But, whatever the beam angle, the depth of water, or the rate of transmission, the distance of $c\tau/2$ above the sea bed marks a definite boundary under which no sampling is possible at all. This distance is shown against pulse duration in Table 1.

Table 1

Pulse duration (ms)	Resolution distance $c\tau/2$ (m)	Volume of DDZ $m^3 \times 10^3$ per km^2
0.2	0.15	150
0.4	0.3	300
0.6	0.45	450
0.8	0.6	600
1.0	0.75	750
1.2	0.9	900

For each transmission, the volume is that of a frustrum of a cone where the height, H of the frustrum is $c\tau/2$. In terms of θ, the depth, and the pulse length it can be expressed as

$$V = 0.134\ c\tau\ [(2d\tan\theta/2)^2 + ((2d-c\tau)\tan\theta/2)^2 + (2d\tan\theta/2)(2d-c\tau)\tan\theta/2]\ m^3$$

where θ, d, c, τ are as before.

But for each km^2 of survey area, the total volume of water near the sea bed which cannot be sampled is $5 \times 10^5 c\tau$ (m^3); this is given in Table 1 for pulse durations of 0 to 1.2 ms. It clearly emphasises the need for the shortest possible pulse duration in order to minimize this zone which could be designated as the definite dead zone (DDZ).

In certain areas and for particular periods, e.g. dawn to dusk, some species of pelagic shoaling fish distribute themselves as close to the sea bed as possible where they are often completely within the DDZ. According to Van Olst and Hunter (1970) the maximum packing density in a school occurs with approximately 0.2 body lengths between adjacent fish, but a more normal density would be about 0.5 body length spacing. Cook and Rushworth (1978) assumed that individuals of equal size arrange themselves in parallel rows and if their width and dorsiventral dimensions are equal to about 0.2 of the body length an approximate shoaling density 'P' can be calculated from

$$P = 5.2/L^3 \text{fish}/m^3$$

where L is the length of fish in metres and the number of body lengths (n) between individual fish is 0.2.

When n is increased to 0.5

$$P = 1.36/L^3 \text{fish}/m^3.$$

If we consider 'full' herring with a mean length of 30 cm and weight of 260 g an estimate can be made of the number and hence weight of fish possibly contained within the DDZ. For $n = 0.2$ the maximum number/m^3 = 193; at the spacing of 0.5 the number reduces to 50/m^3.

Assuming a pulse duration of 0.5 ms, Table 1 shows a DDZ of $375 \times 10^3\ m^3$ per km^2 of survey area. Thus the total numbers might be 7.2×10^7 or 1.87×10^7, yielding weights of 18720 tonnes, or 4875 tonnes, respectively. Reducing the echo-sounder pulse duration to 0.1 ms will reduce the DDZ to 75×10^3 per km^2 so, assuming the same densities as above, the numbers likely to be missed are 1.44×10^7, or 0.375×10^7, corresponding to weights of 3744 and 975 tonnes respectively, only 20% of the previous figures.

5. THE EFFECT OF A ROUGH SEA BED

When the sea bed is rough, or uneven, the DDZ will effectively start at a point $c\tau/2$ above the highest object or contour which is acoustically significant. This point is the seabed depth reference for the particular transmission and may increase the overall DDZ in relation to the mean level of the actual sea bed.

Probably the most significant effect of a rough, uneven sea bed is the introduction of amplitude fluctuations, or even discontinuities, into the seabed echo. This complicates the discrimination between fish echoes and echoes from objects, or surfaces, comprising the sea bed. It also means that the seabed echo may be quite unsuitable for use as a reference in seabed-locked signal processors under these conditions.

6. A SLOPING SEA BED

When the slope of the sea bed changes significantly with respect to the axis of the acoustic beam, i.e. they are no longer mutually perpendicular, the volume of the water decreases where effective detection can be made, because the outer edges of the beam approach the sea bed first. In this situation, fish close to the sea bed, but still in a zone where detection is possible, will be in regions of the beam containing lower transmitted energy and having lower receiving sensitivity than on the axis. The greater the slope the less favourable are the conditions for acoustic detection of fish. As the gradient increases, so the final spherical detection cap moves from the centre of the beam along the arc of the pulse wavefront towards the side of the beam nearest to the sea bed. The volume of the dead zone will increase as the gradient increases.

7. NEAR SURFACE DETECTION

The water surface is often moving in a random manner, thus reflecting significant amounts of acoustic energy in directions other than those from which it arrived. Therefore it is difficult to use this surface as a reliable reference, either in terms of its distance from the upward facing towed transducer, or in the stability of the amplitude from its echo for signal processing. This means that, when looking upwards to the surface the DDZ is extended by, at least the wave height, but because of the irregular motion of the surface the actual distance is difficult to define. However, under such conditions it is unlikely that many fish will be found so close to the surface.

In many species of fish the ventral surface target strength is likely to be below that of the dorsal aspect, thus diminishing the amount of acoustic energy returned from the fish.

8. DISCUSSION

The difficulties in making an acoustic survey of fish distributed close to the sea bed can be reduced by using a short duration pulse and by using a narrow-beam transducer, or by towing one of conventional beam width at a suitable distance above the sea bed.

It is clear that the statistics of sampling change rapidly as the pulse gets close to the sea bed, but some form of control can be exercised by optimising the beam overlap where conditions permit. Special care is needed in the interpretation of results when working over rough ground or steeply sloping sea beds.

APPENDIX

1. The volume of the frustrum of a cone, equation 5, is derived from

$$0.268H(D^2 + d_1^2 + Dd_1)$$

where H = height of the frustrum
D = diameter at base
d_1 = " " top.

2. The volume of the cap of a sphere, equation 6, is adapted from

$$(\pi/3\ h_1^2)\ (3\ R_1 - h1)$$

where h1 is the height of the arc
R_1 is the radius of the sphere.

List of symbols

c = speed of acoustic wave propagation
D = diameter of the base of a cone
dl = " " " top of a frustrum of a cone
d = depth of water from transducer face to sea bed
DDZ = definite dead zone
IDZ = indefinite dead zone
n = number of body lengths between fish
g = weight in grams
H = height of frustrum of a cone
hl = height of the arc in a cap of a sphere
m = metre
m/s = metres per second
ms = milliseconds
τ = duration of pulse in seconds
P = number of fish (m^3)
SL = source level at 1 m range on the acoustic axis with a reference intensity of a plane wave of RMS pressure 1μPa. (dB/1μPa/m)
SRT = sensitivity of a receiving transducer in dB relative to 1 volt when subjected to a reference intensity plane wave of RMS pressure 1 μPa (dB/1V/1μPa)
R_1 = the radius of a sphere

ECHO INTEGRATOR THRESHOLD AND FISH DENSITY DISTRIBUTION

by

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ABSTRACT

The effects of threshold levels on integrated echo energy for different fish densities and different echo sounding system performances are investigated theoretically. It is shown that the use of low performance systems may lead to significant underestimates at low fish densities. The system performance required to minimize such effects is computed. Results from repeated field measurements on low density (scattered) and high density (schooled) distributions of sprat using low performance sounding systems are presented and discussed. These results support the theoretical findings.

RESUME

Les effets des niveaux de seuil sur l'énergie réfléchie intégrée pour différentes densités de poisson et différentes performances de systèmes d'écho-sondage sont examinés sur le plan théorique. On montre que l'utilisation de systèmes à basses performances peut mener à des sous-estimations significatives aux faibles densités de poisson. La performance du système nécessaire pour minimiser ces effets est calculée. Des résultats de mesures de terrains répétées sur du sprat à faible densité (dispersé) et à haute densité (en bancs) obtenus en utilisant des sondeurs acoustiques à basse performance sont présentés et discutés. Ces résultats pratiques confirment les conclusions théoriques.

List of symbols

B - Bandwidth
b - Directivity pattern function of a sound beam
c - Sound velocity
d - directivity index
DI - 10 log d (dB)
g - gain at max. time varied gain
I_o - Intensity of transmitted sound at acoustic axis 1 m from the source
I_{eo} - Sound intensity 1 m from the reciever for an echo originating from a single target at the acoustic axis.
I_n - The intensity of noise in a 1 Hz band around the center frequency of the receiver, measured 1 m from the receiver.
k - Voltage response
M - Integrated echo intensity (integrator reading) per sailed distance
NL - Noise spectrum level = 10 log I_n (dB)
R - Range (distance from source)
SL - Source level = 10 log I_o (dB)
TS - Target strength = 10 log $\sigma/(4\pi)$ (dB)
T - Threshold effect = relative loss of integrated echo intensity due to the threshold.
U - Voltage
α - Sound absorbtion term (dB per m)
β - $0.23 \cdot \alpha$
θ - Angle relative to acoustic axis
ρ - Area density of fish
$\sigma/(4\pi)$ - Acoustic scattering cross section
τ - Pulse duration
ϕ - Angle relative to a plane defined by the acoustic axis and a reference direction.

Ω - Solid angle
Ω_o - The solid angle covering an "equivalent ideal beam".

log is used for the logarithm with base 10.

1. THE THRESHOLD EFFECT

When using echo integrator systems for estimation of fish densities, energy contributions from noise are unwanted. Therefore it is common to set a threshold eliminating signals falling below a preset voltage level at the echo integrator input. Simultanously fish echoes falling below the threshold are eliminated. Therefore, the integrator value is a function, M(t), of the threshold.

When there is no noise and no threshold, each fish contributes to the integrator value according to its position in the beam. Then the integrator value can be expressed as

$$M_o = I_o \cdot k \cdot g \cdot \frac{c\tau}{2} \int^{\Omega} b^2(\theta,\phi)\, d\Omega \cdot \frac{\sigma}{4\pi} \cdot \rho \qquad (1)$$

$$= K \cdot \Omega_o \cdot \rho$$

(Forbes & Nakken, 1972)

The loss when using a threshold is then $M_o - M(t)$. It may be convenient to define the "threshold effect" as the relative loss due to the threshold:

$$T = \frac{M_o - M(t)}{M_o} \qquad (2)$$

This function should ideally be close to zero but may in the worst cases reach 1.

1.1 Single fish distributions

Consider fishes which are randomly distributed horizontally but only giving single fish echoes (never more than one fish within the resolution volume). For simplicity all fishes are assumed to be at the same depth and to have equal scattering cross section. In this situation only the fishes occurring inside a certain "threshold position" of the beam are able to give echoes reaching the threshold level, thus being integrated.

This threshold position is convenient to define as a number of decibels out from acoustic axis in the two way directivity diagram for the beam:

$$i_t = -10 \log \frac{b^2(\theta_t,\phi_t)}{1}$$

where θ_t and ϕ_t is all combinations of θ and ϕ where the fish gives an echo level equal to the threshold level.

After a sufficient number of soundings, the accumulated number of fishes will be uniform throughout the cross section of the beam (if the fishes do not have any directional response to the passing of the vessel).

The integrator value may then be expressed as

$$M(t) = K \int_{\Omega=0}^{\Omega_t} b^2(\theta,\phi)\, d\Omega \cdot \rho \qquad (3)$$

where Ω_t is the solid angle covering the area within the intensity isoline number i_t. The threshold effect is then

$$T = \frac{M_o - M(t)}{M_o} = \frac{\Omega_o - \int_{\Omega=0}^{\Omega_t} b^2(\theta,\phi)\, d\Omega}{\Omega_o} \qquad (4)$$

In Figure 1 the threshold effect is plotted against threshold position. This curve is calculated using the approximation that Ω is proportional to i_t, which means that the area between decibel lines is constant throughout the beam. This is a fairly good assumption for the main lobe of ordinary transducers.

1.2 Various distributions of multiple scatterers

Fishes occurring within the same resolution volume give overlapping echoes. The resultant echo level depends on the number of fishes, the phase-difference between single echoes and the position of the fishes. When the phase-differences are random, the expected resultant-echo from n fishes within the resolution volume can be expressed as

$$I_{eo} \cdot \sum_{i=1}^{n} b^2(\theta_i, \phi_i)$$

where θ_i, ϕ_i is the position of fish no. i. This means that the echo level will reach the threshold level when the resolution volume contains sufficiently many fishes in sufficiently favourable positions of the beam.

For evaluation of the threshold effect, we make the assumption that within all resolution volumes containing fish there are n fishes behaving acoustically as one target. Then the echo intensity is $n \cdot I_{eo} \cdot b^2(\theta,\phi)$. The threshold position for this "target" is therefore moved 10 log n decibels further out from the acoustic axis, compared to the single fish situation. The threshold effect is calculated as function of n and shown in Fig. 2 for three different thresholds. The assumptions made are most realistic for schools with small extension compared to the beamwidth. For scattering layers the number of fishes per resolution volume may vary from one to some hundred within the same transmission, and the fishes do not behave acoustically as one target.

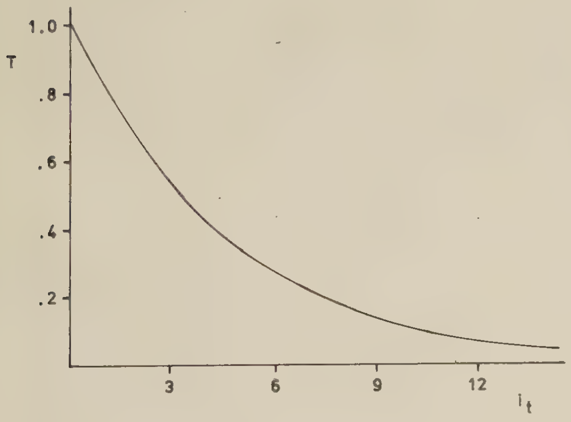

Fig. 1. Threshold effect, T, as function of threshold position, i_t (dB).

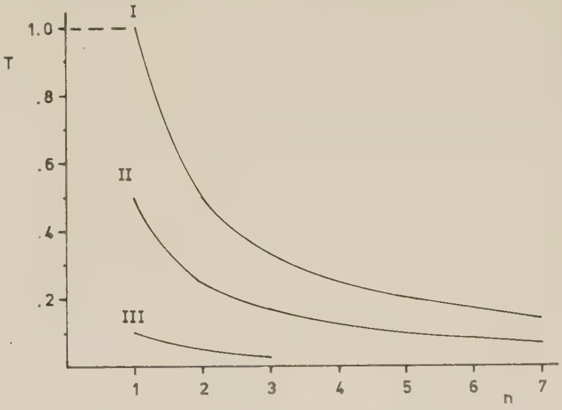

Fig. 2. Threshold effect, T, as function of the number, n, of fishes in the resolution volume.

I: Threshold position (for single fishes) at acoustic axis.
II: Threshold position 3 dB out from acoustic axis.
III: Threshold position 10 dB out from acoustic axis.

The possibility that the threshold will be reached in a given resolution volume, increases with increasing volume density of fish. The threshold effect thus will decrease with increasing volume density in a trend like that shown in Fig. 2.

At a given average area density the volume density may vary according to the fish distribution. When using an unfavourable threshold, an evenly scattered fish distribution (close to a single fish situation) will give a high threshold effect while schools or vertically concentrated layers may give no threshold effect. This means that the integrator values obtained from a given area density of fish will vary according to the fish distribution.

1.3 Range dependence of the threshold effect

It is common to apply a time varied gain proportional to $R^2 e^{2\beta R}$ to all echo-signals before echo integration. The total transmission loss is, however, proportional to $R^4 e^{2\beta R}$. Therefore the intensity of signals at the integrator input is proportional to R^{-2}, when considering single targets which are small compared to the beamwidth (while the average echo integrator contribution over many transmissions from a given density of fish ideally is independent of range). A threshold position for single fishes located outside acoustic axis at short range, will move towards the acoustic axis when the range increases and the threshold voltage is kept constant (Fig. 3). Consequently the threshold effect increases with increasing range, at least for a single fish situation. To compensate for this it is desirable to have a threshold intensity proportional to R^{-2} (it means a threshold voltage proportional to R^{-1}) when integrating on scattered layers of fish. The noise will often set limits to how far this can be done.

The range independent threshold voltage (combined with $R^2 e^{2\beta R}$ TVG) will, however, be correct when there is a high possibility that many fishes will occur in the same resolution volume. Then the number of fishes per resolution volume will increase by R^2, thus giving a signal intensity at integrator input which is independent of range.

1.4 Minimizing the threshold effect

All considerations so far assumes single targets with equal target strength. The target strength depends on fish species, fish size and the orientation of the fish relative to the travelling direction of the transmitted pulse (Nakken and Olsen, 1977; Haslett, 1977). It is likely to be a great variation in target strengths beneath a steaming vessel, even for equal sized fishes (Olsen, 1979). In addition there will often be a mixture of single fish echoes and multiple echoes. Therefore it is difficult to calculate the threshold effect for likely field situations. It is, however, possible to find some requirements for minimizing the threshold effect.

Fig. 1 shows that when the threshold position is sufficiently far out from the acoustic axis, the relative loss of echo intensity is insignificant. We therefore may define the part of the beam laying inside a certain intensity isoline as the significant part of the beam. (In Fig. 4 the dB line no 12 is shown to be a useful rule of thumb for some transducers). The threshold effect is neglible when the smallest fish of interest gives an echo reaching the integrator threshold level in all positions within the significant part of the beam. This should be the case even when the fish is at its maximum depth (R_{max}) and at its most unfavorable orientation. The threshold is always limited by the effective sound intensity received from noise ($I_n \cdot B/d$). The requirements may then be formulated as

$$\frac{I_o \cdot b_b^2 \cdot \sigma_{min}}{R_{max}^4 \cdot e^{2\beta R} \, 4\pi} > I_n \cdot B/d \qquad (5)$$

where b_b is the directivity at the border of the significant part of the beam. By taking the log and multiply by 10 we get

$$SL+20 \log b_b + TS_{min} - 40 \log R_{max} - 2\alpha R_{max} > NL + 10 \log B - DI$$

The equations illustrate that while working with small targets at great depths, high source level and low noise level are required.

When a fixed threshold voltage U_t (volt rms) is applied for all depths, the requirements for proper echo integration are

$$\frac{I_o \cdot b_b^2 \cdot \sigma_{min} \cdot k \cdot g}{R_{max}^2 \cdot 4\pi} > U_t^2 \qquad (6)$$

The maximum depth for proper echo integration of single fish distributions is then

$$R_{max} = \frac{b_b}{U_t} \sqrt{I_o \frac{\sigma min}{4\pi} \cdot k \cdot g} \qquad (7)$$

Below this depth the integrator values will depend on the fish distribution.

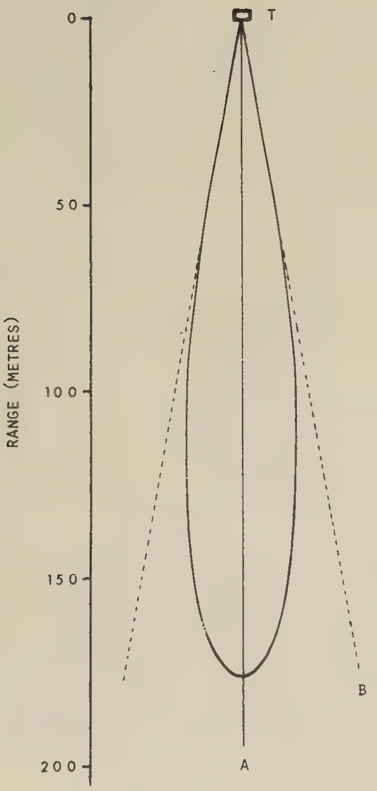

Fig. 3. Threshold position as function of range, when $R^2 \cdot e^{2\beta R}$ time varied gain and constant threshold voltage are applied. The scale of the vertical axis is just an example. A: Acoustic axis. B: Border of the important part of the beam. T: Transducer.

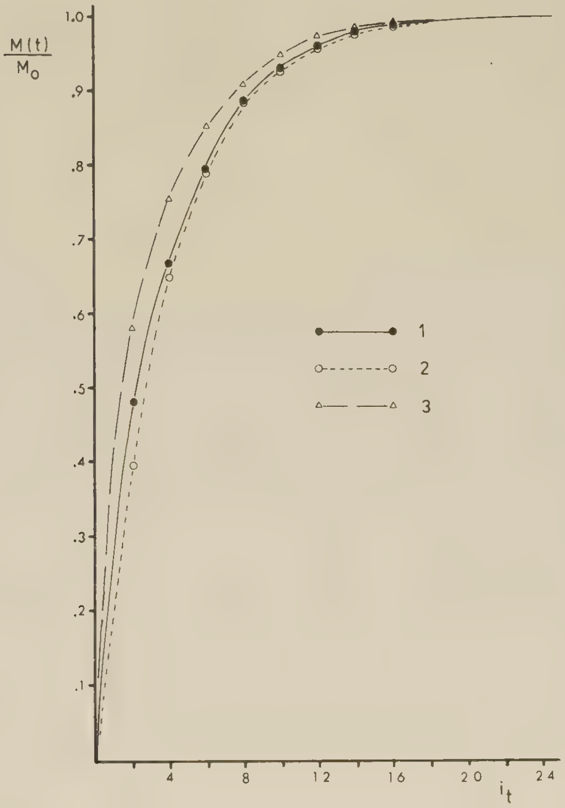

Fig. 4. Relative accumulated echo intensity throughout the beam, $M(t)/M_0$. The abscissa gives the number of decibel lines out from acoustic axis (two-way directivity pattern).
1: Transducer onboard "H. Reusch"/"Daffy".
2: Transducer onboard "P. Rønnestad".
3: Transducer onboard "G.O. Sars".

2. OBSERVATIONS FROM SURVEYS

2.1 Methods

Some data about the surveys are given in the following table:

Vessel	Fish species	Fish size cm	Area
P. Rønnestad	Sprat	5-14 cm	Fjords
H. Reusch/Daffy	Sprat + herring	5-30 cm	Fjord inlet
G.O. Sars	Capelin	5-17 cm	Barents Sea

Both during the surveys with R/V "P. Rønnestad", M/B "H. Reusch" and M/B "Daffy" repeated coverages were made within a small area (from 1 to 30 square nautical miles). With R/V "G.O. Sars" one survey covering most of the Barents Sea were made during September-October each year from 1974-1978. The survey areas with typical survey grids are shown in Aglen (1982).

Table 1 gives technical data and settings for the equipment used.

Table 1. Technical data and settings of acoustic equipment.

	"H. Reusch"/ "Daffy"	"P. Rønnestad"	"G.O. Sars"
Echo sounder	Simrad EY70M	Simrad EK50A	Simrad EK38A
Operating frequency	70 kHz	50 kHz	38 kHz
Bandwidth	2.2 kHz	1.0 kHz	1.0 kHz
Pulse length	0.6 millisec.	0.6 millisec.	0.6 millisec
Transducer, angle between 3dB points	$11.5^{o} x 12^{o}$	$14^{o} x 7^{o}$	$5^{o} x 5.5^{o}$
$10 \log \Psi$	- 16	- 18	- 23
Source level dB//µPa ref 1 m	212.3	215.2	237.0
Voltage response dB//1 Volt per µPa	-91.4	-105.4	-94.5
Time varied gain	$20 \log R + 2\alpha R$	$20 \log R + 2\alpha R$	$20 \log R + 2\alpha R$
Receiver gain	-9dB or -15dB	0dB	-20dB
TVG-range	3-100 m	3-420 m	3-500 m
α applied in TVG	25 dB/km	15.8 dB/km	10.5 dB/km
Threshold voltage (peak)	0.08	0.03	0.005

From the transducer directivity diagrams given by the manufacturer (Simrad A/S) the accumulated echo-intensities are calculated as a function of the number of decibel lines out from acoustic axis. In Fig. 4 this is shown for the three transducers. More than 95% of the total echo intensity is within the 12 inner decibel lines. This area is therefore considered as "the significant part of the beam", which means that $20 \log b_b = - 12$ dB. This and data given in Table 1 are used in equation (7) to give R_{max} as function of TS_{min} for the different equipment:

"P. Rønnestad": $R_{max} = 0.008 \; 10^{0.05 \, TS_{min}}$

"H. Reush"/"Daffy": $R_{max} = 0.039 \; 10^{0.05 \, TS_{min}}$

"G.O. Sars" $R_{max} = 0.225 \; 10^{0.05 \, TS_{min}}$

In Table 4 R_{max} is calculated assuming $TS_{min} = -60$ dB.

2.2 Results

Through all the surveys the fish showed a regular schooling behaviour. During dawn the fish gathered in distinct schools which seemed to keep their formation until dusk, when they dissolved into scattering layers which endured through the whole night. Vertical distribution of the main recordings of fish is shown in Table 2. The fish sometimes tended to stay deeper during day than during night, but this difference was usually small. Almost all recordings were clearly off the bottom.

During the surveys with "P. Rønnestad" the average echo integrator values were always higher during day than during night within the same area. The same tendency was found during the surveys with "H. Reusch" and "Daffy".

When ranking all the density estimates obtained with "Daffy" during March 1978, a Wilcoxon two sample test (Hodges and Lehman, 1970) leads to the conclusion that day estimates are higher than night estimates at 1% significance level. The separate estimates are given by Aglen (1982).

The integrator values obtained onboard "G.O. Sars", however, seemed to be quite similar during day and night. Table 3 shows the ratio between average integrator value obtained during day and the following night for "P. Rønnestad", "H. Reusch" and "Daffy". It also shows the ratio between average integrator value for all days and for all nights during each survey with "G.O. Sars".

Table 2. Vertical distribution of the main fish recordings during the surveys.

Species	Area	Depth of the main recordings (m)
Sprat + herring	fjord inlet	10 - 40
Sprat	fjords	20 - 80
Capelin	Barents Sea	20 - 100

Table 3. Ratio between average integrator values obtained during day ($\bar{M}_D$) and night ($\bar{M}_N$).

"P. Rønnestad" in fjords			"H. Reush"/"Daffy" in fjord inlet		"G.O. Sars" in the Barents Sea	
Place	Time	$\bar{M}_D/\bar{M}_N$	Time	$\bar{M}_D/\bar{M}_N$	Time	$\bar{M}_D/\bar{M}_N$
Eidfjord	Oct. 77	22.3	Sep. 77	.8	Autumn 74	.9
		6.8				
	Jan. 78	4.6	Mar. 78	.7	" 75	1.4
		1.9				
	Feb. 78	9.5		2.0	" 76	.7
		13.1				
	Mar. 78	3.9		2.1	" 77	.9
		3.0				
		3.4		2.1	" 78	1.2
Samlafjord	Jan. 78	5.7				
	Feb. 78	10.5				
		9.9				
Nordfjord	Feb. 78	4.5				
		7.2				
		5.9				
		2.7				
Average		7.2	Average	1.5	Average	1.02

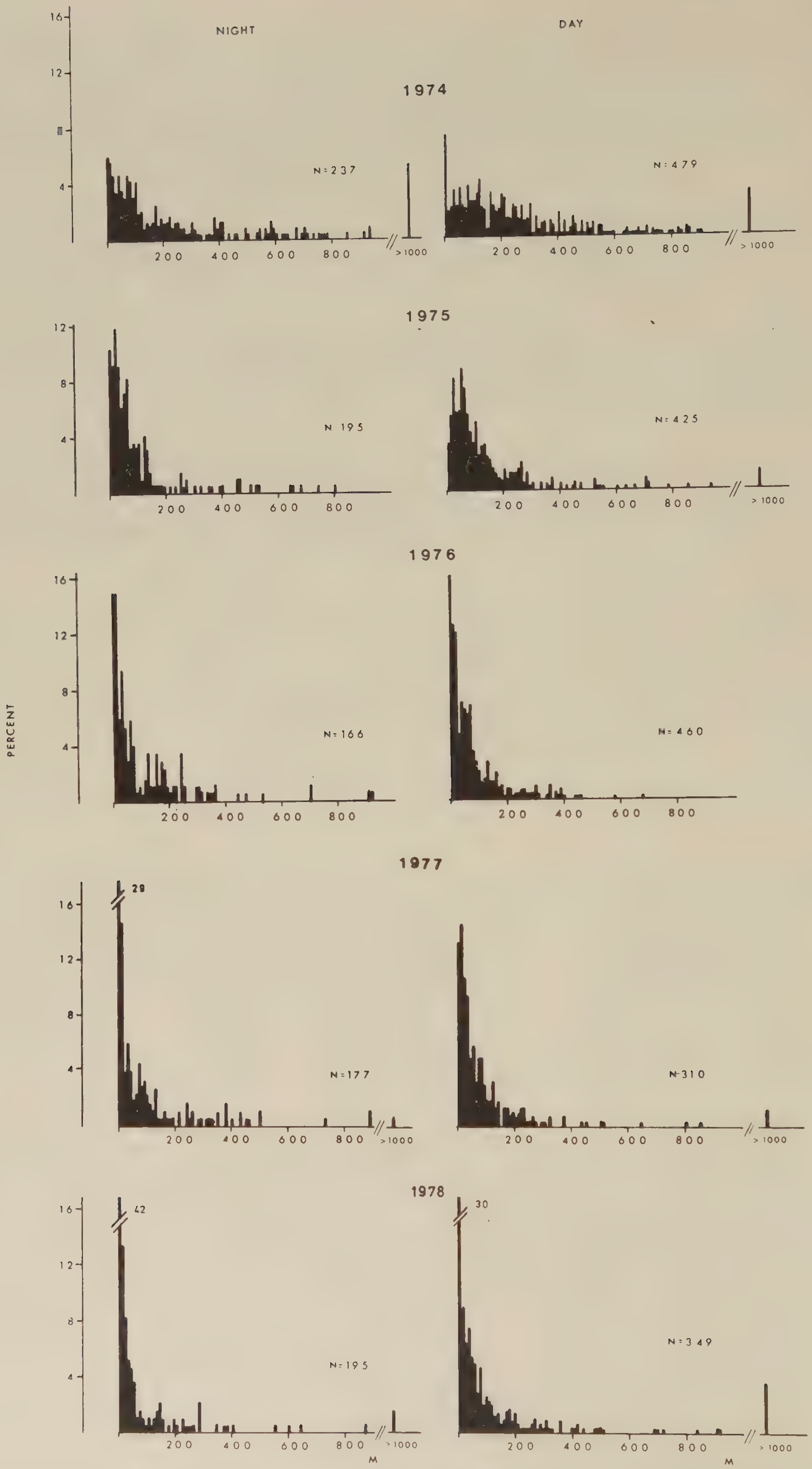

Fig. 5. Distribution of echo integrator values (5 mile averages), M, during the autumn capelin surveys with R/V "G.O. Sars" in the years 1974-1978. N=number of values.

"G.O. Sars" did not operate in the same area during day and night. Therefore the compared average integrator values do not necessarily represent the same average fish density. Fig. 5 shows the distribution of integrator values, averaged over 5 nautical miles, for day and night obtained onboard "G.O. Sars" during each survey. A few very high values have great influence on the mean values of the distributions. Therefore small systematic differences between day and night observations might exist even if the mean values are equal. However, any differences of importance should appear in these comparisons.

3. DISCUSSION

The minimum fish size for this survey was 5 cm. Target strength measurements (Nakken and Olsen, 1977 and Foote and Nakken, 1978) indicate that maximum dorsal aspect target strength for 5 cm fish with gas-filled swimbladder is in the order of -50 dB at 38 kHz and 120 kHz operating frequency. The measurements also show that unfavourable fish aspects may give target strength values considerably below -60 dB. However, as long as a reasonable percentage (say >20) of the fish is favourably oriented (less than about 15° tilted up or down), the relative echo energy contribution from single fishes with $TS < -60$ dB is insignificant. TS-measurements at various frequencies (McCartney and Stubbs, 1971) indicate that this conclusion is likely to be valid at 50 kHz and 70 kHz too. Therefore -60 dB should be a reasonable value for TS_{min} during these surveys.

When comparing the estimated maximum depth for proper single fish integration (Table 4) and the vertical fish distribution (Table 2) one should expect that the results obtained with "P. Rønnestad" at night are seriously influenced by the threshold effect. This may also be the case with the results from "H. Reusch" and "Daffy" but not with the results from "G.O. Sars".

A fish school with a "target strength" of -20 dB (which might be a small school) will theoretically be properly integrated at a depth 100 times the R_{max} given in Table 1. Therefore day time observations from these surveys are not influenced by the threshold.

If the threshold effect is the only reason for the observed differences between integrator values obtained during day, M_D, and night, M_N, (Table 3), then $(M_D-M_N)/M_D$ estimates the average threshold effect during night. This is calculated for each vessel as an average from all surveys and shown in Table 4.

A high threshold effect was observed when R_{max} did not reach down to the main fish recordings, while the threshold effect observed when R_{max} reached below the main fish recordings, was neglible.

These results fit well to the theoretical considerations. However, the ratio between day and night values cannot always be used as an estimator of threshold effect. In many situations the ratio may be seriously influenced by other factors. Such factors are shadowing effect in schools during daytime (Røttingen, 1976; Foote, 1978) and day/night differences in average target strength due to differences in fish orientation or swimbladder shape and volume (Olsen, 1976). In shallow areas a common reason for observing differences between day and night is that during daytime a significant amount of fish tend to stay too close to bottom to give echoes which can be distinguished from the bottom echoes, and during night much fish might be lost above the transducer (Olsen, 1981; Aglen and Iversen, 1980).

Table 4. Observed average threshold effect compared to fish distribution and predicted maximum range (R_{max}) for proper single fish integration.

Vessel	R_{max} (m)	Depth interval for main fish distribution (m)	Observed average threshold effect during night
P. Rønnestad	8	20 - 80	0.9
H. Reusch/Daffy	39	10 - 40	0.3
G.O. Sars	225	20 - 100	0.02

INCREASED PRECISION OF ECHO INTEGRATION RECORDINGS UNDER VARIOUS WEATHER CONDITIONS

by

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ABSTRACT

When observing fish under moderate and bad weather conditions with echo sounders and sonars having hull-mounted transducers, information is lost when the transmitted and received echo energy is attenuated due to wind- and wave-induced bubbles in the surface layer.

When we are performing echo integration surveys under such weather conditions, we have earlier tried by experience to correct the recorded integrator values which are influenced by the excess attenuation from air bubbles. The described method will enable us to improve this correction to a more satisfactory level of accuracy.

We present a brief introduction on the physics of attenuation of acoustic energy from bubbles and their strong influence on echo integration surveys. From the observations from two different research vessels we give results for the total excess attenuation and the corresponding correction factor versus wind velocity at 38 kHz. To demonstrate how this attenuation from bubbles is dependent on frequency, the attenuation at 12 and 120 kHz measured on board one of the vessels is also presented.

RESUME

Quand on observe des poissons dans des conditions climatiques modérées ou mauvaises, avec des échosondeurs et des sonars équipés de transducteurs montés sur coque, l'information se perd lors de la transmission, et l'énergie d'écho reçue est atténuée en raison des bulles provoquées par le vent et les vagues à la surface.

Quand nous conduisons des études d'intégration d'écho dans de telles conditions, nous essayons par expérience de corriger les valeurs d'intégration enregistrées qui sont influencées par l'atténuation excessive causée par des bulles de l'air. La méthode décrite va nous permettre d'améliorer cette correction à un niveau de précision plus satisfaisant.

Nous y présentons une brève introduction à la physique d'atténuation de l'énergie acoustique des bulles et leur influence profonde sur les études d'intégration d'écho. A partir des observations obtenues par les deux différents navires de recherche, nous donnons des résultats pour le total d'atténuation excessive et le facteur de correction correspondant contre la vitesse du vent à 38 kHz. Afin de démontrer comment cette atténuation provenant des bulles dépend de la fréquence, l'atténuation à 12 et 120 kHz mesurée à bord de l'un des navires est également présentée.

1. INTRODUCTION

Within the field of fish stock assessment the application of scientific echo sounders and echo integration techniques has become a tool for fishery researchers. This method of abundance estimation is based on the integration of the backscattered sound energy from aggregations of fish. Applying the knowledge of the effective strength of backscattering per individual or from a known number of fish, the amount of observed fish may be estimated.

Wind- and wave-induced bubbles in the surface layers will cause excess attenuation of the transmitted and received sound energy when using echo sounders having transducers located near the surface (Medwin, 1974; Løvik, 1980). Two possible ways of overcoming these problems are:

- use of a towed transducer placed under the bubble-occupied water column, or
- measurements of the bubble density, and estimation of their size distribution and the attenuation they will cause. The energy loss at transmission and reception may then be compensated for.

When we have observed from the echograms and the echo integrator that the bubbles were influencing the acoustic observations, we have tried to correct the integrator recordings by adding a certain percentage determined on the basis of experience. In relation to our present requirements of precision of acoustic observation methods, we have found this approach unsatisfactory. Towed transducers are now being increasingly used, but for a long time to come and under certain circumstances hull-mounted transducers will still be in use.

For the latter systems we propose to measure the bubble distribution and to estimate the effect on echo sounding and integration. This can be done by measuring the volume backscattered energy in the upper layers with the same echo sounders and transducers as used for fish abundance observation. Fig. 1 shows a sketch of the vessel and the environment.

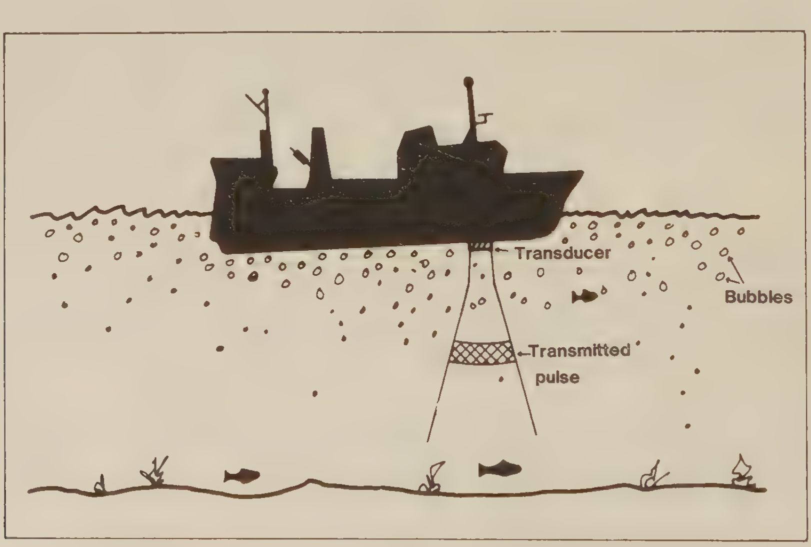


Fig. 1. Vessel and environment.

2. METHODS

2.1 A model for estimating the attenuation due to bubbles from volume reverberation measurements

A coarse description of the model will be given here, for further details see Løvik (1980) and Dalen and Løvik (1981).

Volume reverberation is described by a volume backscattering coefficient, s_v, defined as the backscattering cross section per unit volume. The backscattered sound energy is assumed to add on a power basis, i.e. as incoherent scattering. The reverberation intensity at the transducer, I_r, from a volume V at distance r in the farfield of the transducer is:

$$I_r = \frac{I_0 \, c \, \tau \, s_v \, r_0^2}{2r^2} \int_{\Omega} b_t(\theta,\phi) b_r(\theta,\phi) d\Omega \qquad (1)$$

where

I_0 - source intensity, at r_0

r_0 - reference distance, normally 1 m

c - speed of sound in the medium

τ - pulse length

s_v - volume backscattering coefficient

Ω - solid angle determining the angular coordinates of the observation volume, and

$b_t(\theta,\phi)$ and $b_r(\theta,\phi)$ - the directivity functions during transmitting and receiving modes, respectively. When using stabilized transducers their effect on the observation volume is assumed to be identical and equal to $b(\theta,\phi)$.

The volume V is determined by the pulse length, the speed of sound, the distance from the transducer, and the directivity function.

When the source intensity I_0 and the equivalent solid beam angle Ψ are known, the volume backscattering coefficient can be found by measuring the reverberation intensity.

$$s_v = 2I_r r^2 / I_0 c \tau r_0^2 \Psi \qquad (2)$$

In the case of the reverberation due to bubbles the major part of the backscattered sound is from resonant or near-resonant bubbles, and the volume backscattering coefficient can then be expressed as:

$$s_v = N\sigma_s(a_0)/4\pi \qquad (3)$$

N is the number per unit volume of resonant scatterers having scattering cross sections $\sigma_s(a_0)$ and radii a_0.

The attenuation rate due to bubbles, α_b (db/m), is estimated from the following expression:

$$\alpha_b = K_1 N \sigma_e(a) \qquad (4)$$

where $\sigma_e(a)$ is the extinction cross section of a bubble having a radius a, and the coefficient K_1 is equal to 4.34. According to equations (3) and (4) N has to be found in order to estimate the attenuation from the bubbles.

The extinction cross section is strongly dependent on the damping constant δ which is a function of the frequency and the depth. At frequencies of ordinary applied echo sounders, 12-200 kHz, the thermal damping dominates.

When high wind velocities appear, which produce a large number of bubbles in the upper water column, we must include multiple scattering in the model. The number of resonant bubbles N(x) as a function of the distance from the transducer x, is then given by:

$$N(x) = (n_0 \exp(-kx)/[1 - \frac{2\sigma_e(a)n_0}{k} 1 + \exp(-kx)]) \qquad (5)$$

where n_0 - number of bubbles N(x) at x=0, and

k - a coefficient determining the decrement of the number of resonant bubbles for increasing depth.

The total excess attenuation can be found from the following equation:

$$\alpha_{tb} = 2K_1 \int_{h_0}^{r_1} \sigma_e(a)N(r)dr \qquad (6)$$

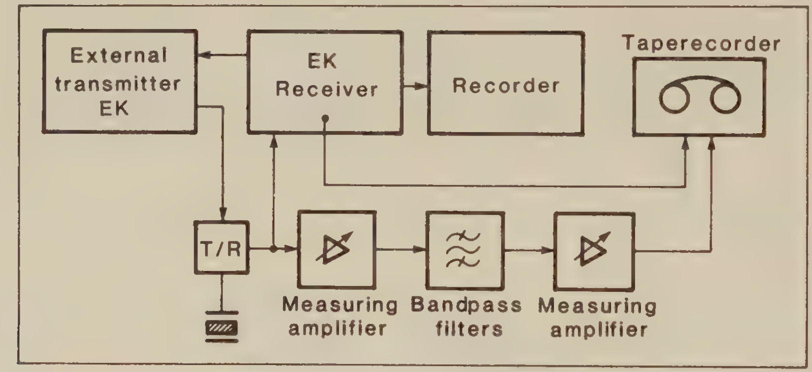
where h_0 is the depth of the transducer and r_1 is the maximum depth to which we observe bubbles.

2.2 Measurement of the Volume Reverberation

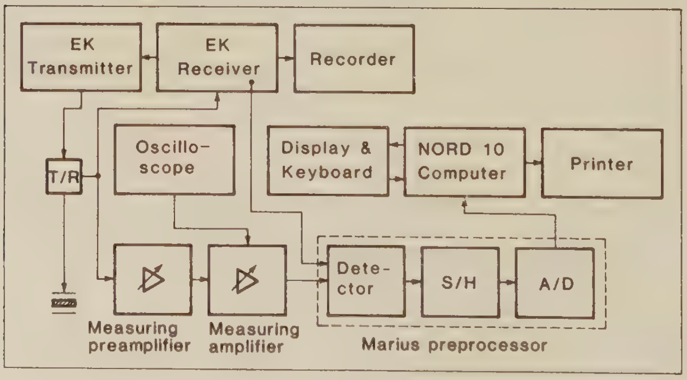
The measurements from the two vessels were carried out as follows:

a - R.V. "G.O. Sars" - during two cruises in 1978 at the frequencies 12, 38 and 120 kHz,

b - R.V. "Johan Ruud" - during three cruises in 1981 at 38 kHz.



a) R.V. "G.O. Sars"



b) R.V. "Johan Ruud"

Fig. 2. Instrument set-up for bubble attenuation studies.

The applied echo sounders were all of the type SIMRAD EK, Scientific Echo Sounders. The received signal was taken out of the receiver just after the transmit/receive switch. Two different instrument set-ups were used as shown in Fig. 2 (Berg, 1981). The transducers on board R.V. "G.O. Sars" were stabilized while this was not the case for the R.V. "Johan Ruud".

3. ESTIMATES OF THE ATTENUATION FROM BUBBLES AND THE CORRECTION FACTOR FOR THE INTEGRATOR VALUES

The total mean attenuation from bubbles estimated by equation (6) and measurements at 12, 38 and 120 kHz from R.V. "G.O. Sars" is shown in Fig. 3.

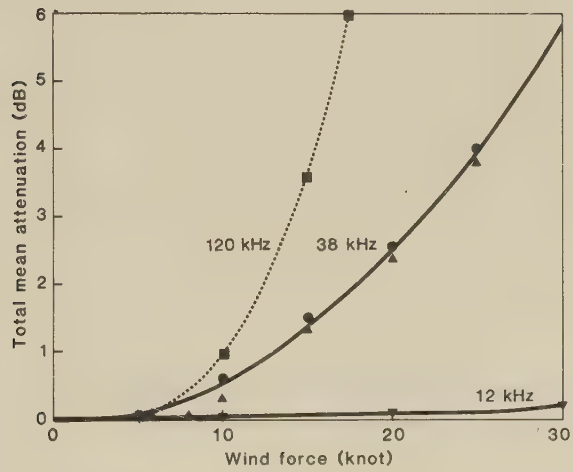


Fig. 3. Total mean attenuation from bubbles versus wind velocity at 12,38 and 120 kHz based on the reverberation, and on the bottom integration data (Δ).

This specific attenuation can also be observed by having an integrator working on a bottom layer of constant thickness. We require that the acoustic macro-characteristics of this layer undergo just minor and continuous variations within the surveyed area. Greater variations of the integrator readings from this layer can then be related to changes of the attenuation caused by bubbles in the water column. Such measurements were done at 38 kHz on board R.V. "G.O. Sars" in the winter 1977 in the Barents Sea (Dalen and Løvik, 1981). The results are indicated by the legend "Δ" in Fig. 3. The results from the two different and independent methods agree very well over the common range of wind velocities.

Fig. 4 shows the total mean attenuation versus wind force at 38 kHz from the R.V. "Johan Ruud".

In Fig. 5 the correction factor to be applied on the integrator recordings on board the two research vessels are displayed. When the integrator values are recorded in linear scale, they should be multiplied by the wind- and weather-determined correction factor. As an example from "G.O. Sars" the observed integrator values at mean wind velocities of about 22 knots should be multiplied by 2 or when the integrator values are recorded as mean volume backscattering strengths, $\bar{s}_v$, in decibels, they should be corrected by adding a correction of 3dB.

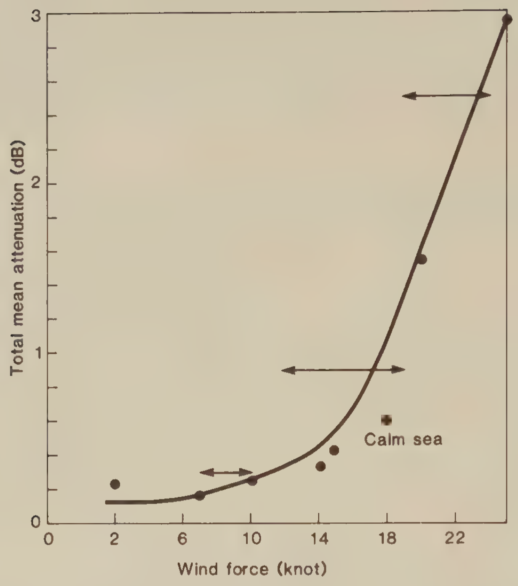


Fig. 4. Total mean attenuation from bubbles versus wind velocity at 38 kHz from R.V. "Johan Ruud".

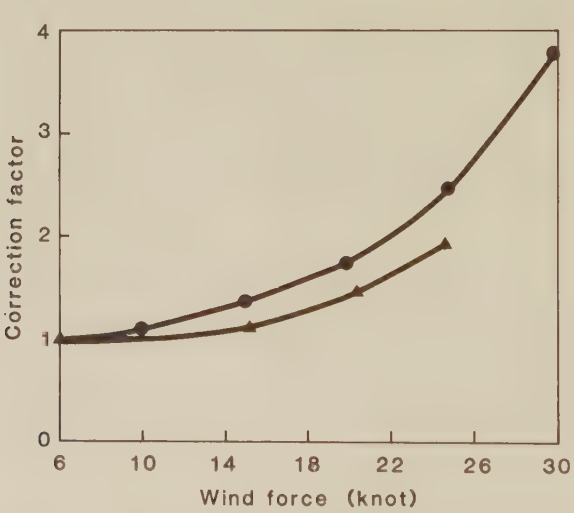


Fig. 5. Correction factor for integrator recordings at 38 kHz. R.V.s "G.O. Sars" (o), and "Johan Ruud" (Δ).

4. A BUBBLE ATTENUATION ESTIMATOR

As seen from Figs 3 and 4 the attenuation from bubbles will vary from vessel to vessel. From the whole context, i.e. different wind and wave motion patterns of the vessels, different depths of their transducers, and stabilized or non-stabilized transducers, this should be so.

In order to fulfill the to-day requirements of accuracy of acoustical fish abundance estimation methods, research vessels having hull-mounted transducers, should be equipped with a bubble attenuation estimator. The concept we are working at is sketched in Fig. 6. The estimator shall either be operated as an independent unit, or together with digital integrators, or even in time to come as a built-in unit of the integrator.

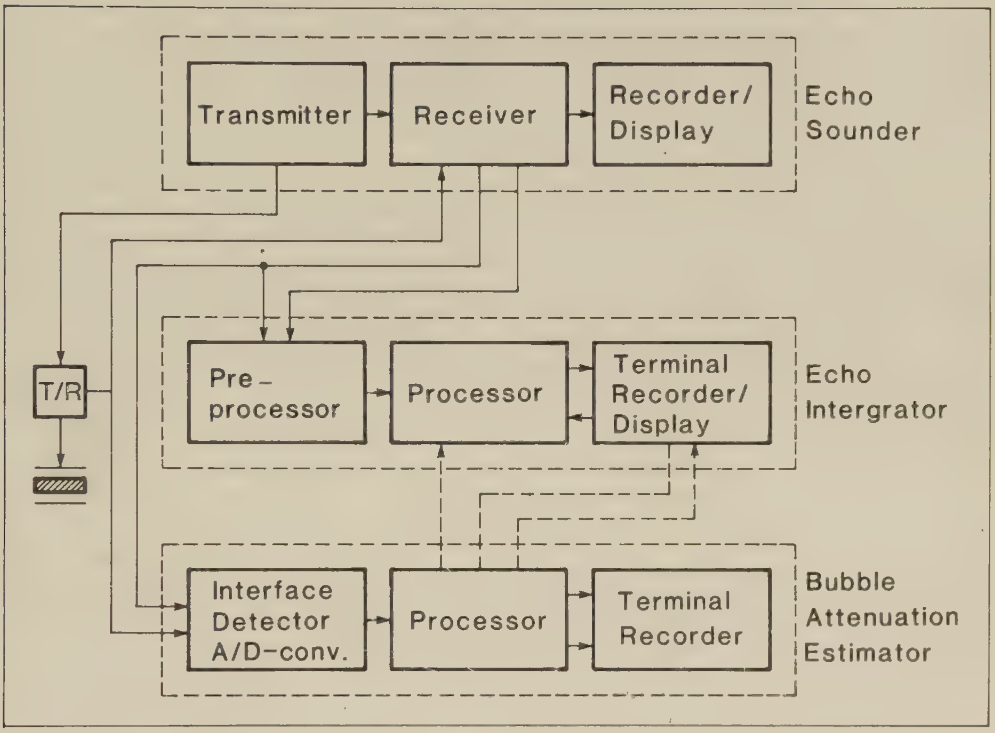


Fig. 6. The Echo Integrator and Bubble Attenuation Estimator.
the 1982-version, --- possible future configuration.

USE OF ELASTIC SPHERES AS CALIBRATION TARGETS

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ABSTRACT

The theory of acoustic scattering by solid elastic spheres is reviewed. This is applied to electrical-grade copper and to tungsten carbide with 6% cobalt binder to determine the diameters of spheres for calibration of 38 kHz echo sounders when a target strength of the order of -41.5 dB is required. The nominal target strengths of the derived 30.4 mm copper sphere and selected 38.1 mm tungsten carbide ball bearing are, respectively, -40.7 and -42.4 dB. These are confirmed by measurement. A further theoretical study establishes the stability of these target strengths and, more importantly, demonstrates the possibility of maintaining the precision of calibrations under variable environmental conditions with either of the spheres.

RESUME

La théorie de la réflexion acoustique par des sphères solides et élastiques est revue. On l'applique au cuivre de qualité électrique et au carbure de tungstène avec 6 % d'un liant cobalt afin de déterminer les diamètres des sphères pour l'étalonnage d'échosondeurs à 38 kHz lorsqu'un index de réflexion de l'ordre de - 41,5 dB est nécessaire. Les indices de réflexion des sphères en cuivre de 30,4 mm et la bille en carbure de tungstène de 38,1 mm sont respectivement - 40,7 et - 42,4 dB. On confirme ces résultats par des mesures. Une autre étude théorique démontre la stabilité des index de réflexion et surtout la possibilité de conserver des étalonnages précis dans des conditions variables d'environnement avec les deux sphères.

1. INTRODUCTION

The importance of hydroacoustic equipment calibration in fisheries research can hardly be overstated. The penalty for poor calibration is loss of certainty in all absolute measurements, both in the primary estimates of fish density along survey tracks and, ultimately, in the secondary estimates of fish abundance in the surveyed area.

An expedient means of calibrating echo sounders and echo integrators is obtained with spheres employed as passive targets (Wallace et al., 1975). Examples include ping pong balls (Welsby and Hudson, 1972; Traynor and Ehrenberg, 1979), glass and plastic spheres (Hashimoto and Maniwa, 1956; Shibata, 1970), and both hollow and solid metal spheres (Traynor and Ehrenberg, 1979; Dragonette et al., 1981; Foote et al., 1981). The general problem with passive targets is knowing what the target strength is, preferably a priori. Copper and tungsten carbide are especially advantageous in this respect. In addition to being physically rugged, their densities and elastic constants are well enough known to permit the calculation and control of sphere target strengths.

We show in this paper how the various properties of electrical-grade copper and tungsten carbide with 6% cobalt binder can be exploited in the design of calibration spheres. We consider the particular example of calibrating 38 kHz echo sounders using a sphere 5 m from the transducer. This application requires a target strength of the order of -41.5 dB.

The basic theory of acoustic scattering by solid elastic spheres is first reviewed. This is applied to each material and the sphere diameters are determined. Measurements supporting these designs are cited. Theory is further applied in an investigation of the target strength stability. It is shown that precision calibrations to within 0.1 dB are possible by means of such spheres.

2. THEORY

The problem of acoustic scattering by solid homogeneous elastic spheres was first considered by Faran (1951). His expression for the monochromatic backscattering amplitude F, as developed by Hickling (1962) and corrected by Goodman and Stern (1962), has formed the basis for much subsequent work. The principal dependences of F are:

$$F = F(a,\rho_1,c_1,c_2,\rho,c,\omega) \qquad (1)$$

where a is the radius of the sphere, ρ_1 is its density, c_1 and c_2 are the longitudinal and transverse sound speeds, respectively, ρ is the density of the immersion medium, c is its sound speed, and ω is the frequency of the acoustic wave.

Hickling (1962) extended the scattering model to pulsed signals. For an incident signal with the Fourier spectrum $S(\omega)$, the backscattered signal is:

$$p_{bsc}(t) = FT^{-1}\ (SF) \qquad (2)$$

where the Fourier transform operator $FT^{-1}(\cdot)$ transforms the argument from the frequency to time domains.

The final stage in the model development incorporated the effects of signal processing in the receiver (Foote *et al.*, 1981; Foote, 1982; MacLennan, 1982). According to the linearity assumption underlying (2), the received signal is:

$$p_{rec}(t) = FT^{-1}\ (SFH) \qquad (3)$$

where $H(\omega)$ is the frequency response function of the receiver.

The importance of both the shape of the incident signal waveform and the characteristics of the receiver on the observed form of the echo is thus evident (Foote *et al.*, 1981; MacLennan, 1981). The consequence for the conventional definition of target strength (Beranek, 1972) is less evident but no less significant. The intensities in the cited definition must be replaced by energies. After some mathematical manipulation, the expression for the backscattering cross section σ becomes (Foote *et al.*, 1981; Foote, 1982):

$$\sigma = 4\pi \int_0^\infty |SFH|^2 d\omega \Big/ \int_0^\infty |SH|^2 d\omega \qquad (4)$$

The usual relationship between σ and the target strength TS is maintained, but σ is now defined as in (4):

$$TS = 10 \log \sigma/4\pi \qquad (5)$$

3. APPLICATIONS

Equation (4) is easily evaluated for the purpose of designing calibration spheres. This is done below for two different spheres intended for the calibration of 38 kHz echo sounders when a target strength of the order of -41.5 dB is required. The elements common to each computation, the factors S and H, are now described.

For the ordinary pulsed sinusoidal transmission of the echo sounder, the incident signal spectrum S has the simple form:

$$S(\omega) = \frac{\sin(\omega + \omega_o) T/2}{\omega + \omega_o} + \frac{\sin(\omega - \omega_o) T/2}{\omega - \omega_o} \qquad (6)$$

where ω_o is the centre frequency and T is the duration of the transmit pulse. This is transformed successively by the process of echo formation and by filtering in the course of echo reception.

This last process is characterised by the frequency response function H. For computational purposes, H may be expressed either analytically by analysis of the equivalent circuit of the acoustic system, essentially a transformer-coupled transducer (MacLennan, 1981), or through the measured function (Foote et al., 1981; Foote 1982). The approaches are consistent and agreement with experiment has been excellent.

To illustrate the nature of H, measurements on the EK-400/38 echo sounder, performed by R. Brede and R.L. Nielsen of Simrad, are presented in Fig. 1. It is this function which is assumed in the computations reported below.

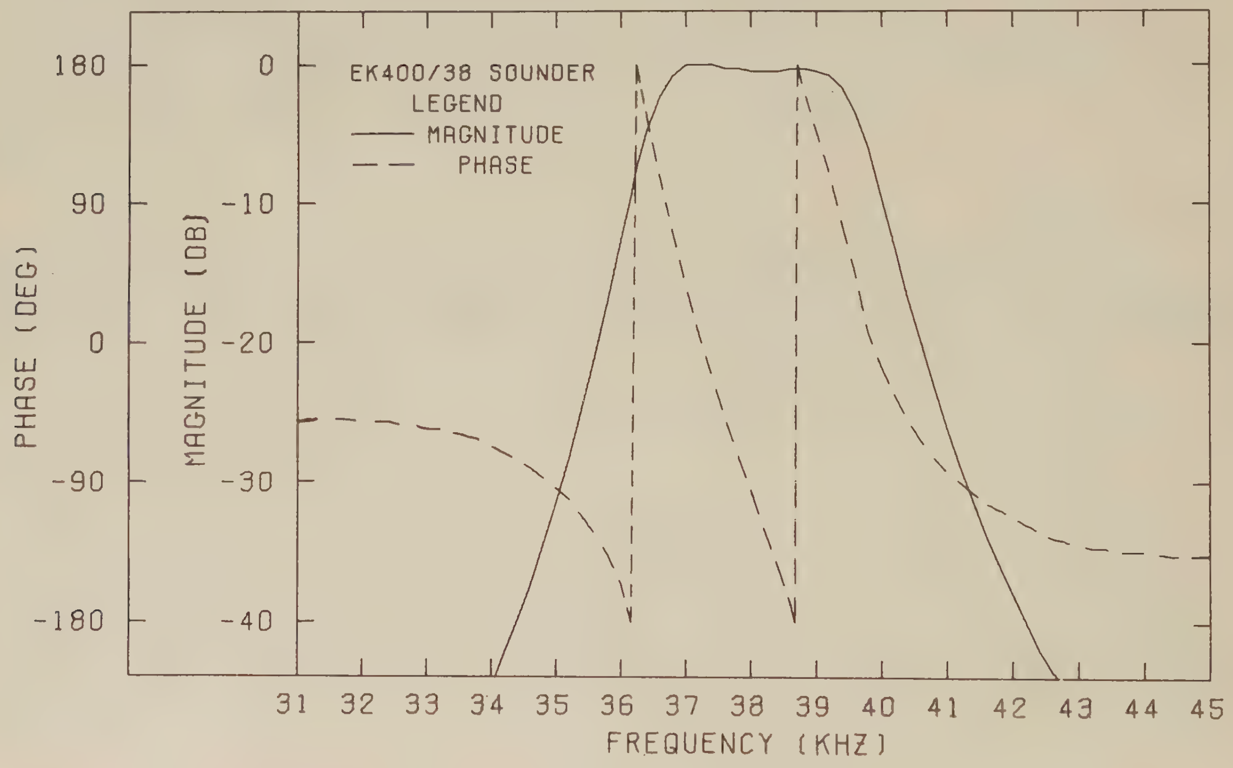

Fig. 1. Measured receiver frequency response function of the Simrad EK-400/38 echo sounder.

The third factor in (4) is the monochromatic backscattering amplitude F. This depends on characteristics of the sphere and the medium in addition to the frequency. The influence of these on the target strength is now considered in two schemes for the selection of materials and sizes of calibration spheres.

3.1 Copper

Electrical-grade copper is an excellent material for calibration spheres (Foote et al., 1981; Foote, 1982). It has noble physical and chemical properties which resist corrosion in sea water. Copper is conveniently available in a highly pure state. It is cheap and machinable. Thus its elasticity can be exploited to derive spheres with a wide range of target strengths (Foote and MacLennan, 1982). This is illustrated here for electrical-grade copper with the following characteristics; $\rho_1 = 8947$ kg/m^3, $c_1 = 4760$ m/s, and $c_2 = 2288.5$ m/s.

In view of the diverse acoustic surveying activities of the Institute of Marine Research, it was decided to determine the sphere diameter to minimise variations with temperature in the range 0 to 30°C in sea water of nominal salinity 35 ppt. The optimisation:

$$\left.\frac{d\sigma}{d\tau}\right|_{\tau_o} = 0 \qquad (7)$$

was performed where τ is the temperature variable and τ_o is a reference temperature in the range $(0,30)^{o}$C (Foote _et al._, 1981; Foote, 1982^{o}). The specification of the approximate target strength makes the solution unique. The initial work required a target strength of the order of -35 dB for calibration of hull mounted transducers when the target range is relatively large. This led to the 60 mm copper calibration sphere.

However, the present exercise requires a target strength around -41.5 dB. In this case the solution is a sphere diameter of 30.4 mm for a reference temperature of 12°C.

3.2 Tungsten carbide

Tungsten carbide is extremely hard, 9.5 on the Mohs hardness scale. This has long been regarded as a highly desirable property for calibration spheres (Chivers and Anson, 1982). The hardness makes machining impractical, but sintering in the spherical shape is a well-established, precision process. The availability of tungsten carbide ball bearings makes their choice for calibration spheres natural. What may be lost by not optimising the diameter in the manner of (7) may be regained by the superior hardness of tungsten carbide. This renders it less sensitive to variations in material parameters, although not to variations in other parameters.

For the present application it was convenient to make a selection from a standard range of ball bearings composed of sintered tungsten carbide with 6% cobalt binder. The material properties of this alloy are: $\rho_1 = 14900$ kg/m^3, $c_1 = 6864$ m/s, and $c_2 = 4161.2$ m/s (Gerlich and Kennedy, 1979). Computation of σ from (4) assuming a temperature of 10°C and salinity of 35 ppt, hence a water density of 1027 kg/m^3 (Dietrich, 1952) and sound speed of 1490 m/s (Del Grosso, 1974), allows the target strength to be determined as a function of sphere diameter. Given the requirements that the target strength be near -41.5 dB and that the sphere be procurable as an off-the-shelf item, the 38.1 mm diameter ball bearing was selected.

4. RESULTS

The theory of acoustic scattering by solid elastic spheres has been thoroughly confirmed by a long and apparently continuing series of experiments, which have been reported largely in the _Journal of the Acoustical Society of America_, since the study of Hampton and McKinney (1961). For present purposes it is sufficient to mention the studies which have provided direct confirmation of the acoustic properties of copper and tungsten carbide spheres.

Experimental work on electrical-grade copper has been described in Foote _et al._ (1981) and Foote (1982). The various measurements reported there have included both direct measurements of absolute target strengths by means of intercepting hydrophones and indirect measurements based on comparison with a target of constant but unknown target strength. Examples of this second kind of measurement with application to other materials are contained in Foote (1981). The agreement between measurement and theory for copper calibration spheres is around 0.1 dB. Direct absolute measurements with a calibrated EK-38 echo sounder have confirmed the theory to within about 0.2 dB. The lower precision here is due to extraneous factors. The measurements were made by J.E. Nygaard and A. Romslo on RV "Michael Sars" during January 1982.

Confirmation of theory by measurement for tungsten carbide spheres is at least as good. Dragonette _et al._ (1981) provide an exceptional example of precision measurement. Indirect measurements on 38.1 mm tungsten carbide ball bearings, using the 60 mm copper sphere as a reference, have agreed with theory to within 0.1 dB (MacLennan, 1982).

5. STABILITY OF TARGET STRENGTHS

In order to facilitate precision calibrations, the target strength of the sphere should be reasonably constant with changing conditions. The magnitude of variation should be known for each variable. Should the variation exceed the required degree of accuracy, then a correction may be applied to take account of the exact conditions during the calibration and restore its theoretical precision. Such considerations are represented by the term "stability", which we now consider for the particular cases of the subject calibration spheres.

The target strength of any sphere may vary with changes in any of the material, medium, or equipment parameters. Since the material properties of the copper and tungsten carbide spheres are dissimilar, while the medium and equipment parameters are common to both, these two sets of parameters are considered separately. During each variation, the other parameters are assumed to be constant. The nominal reference values about which the respective variations are performed are presented in Table 1.

Table 1. Nominal values of parameters during single-parameter variations.

				Sphere	
Type	Parameter	Symbol	Units	CU30.4	WC.38.1
Sphere	Diameter	$2a$	mm	30.4	38.1
Sphere	Density	ρ_1	kg/m^3	8947	14900
Sphere	Longitudinal sound speed	c_1	m/s	4760	6864
Sphere	Transverse sound speed	c_2	m/s	2288.5	4161.2
Medium	Density	ρ	kg/m^3	1027	
Medium	Sound speed	c	m/s	1490	
Equipment	Centre frequency	f	kHz	38.0	
Equipment	Pulse duration	T	ms	1.00	

A careful reading of the literature on copper (Foote, 1983 and on tungsten carbide with 6% cobalt binder (Foote and MacLennan, 1982) suggests that the variation of density will not exceed 1%; of longitudinal sound speed, 5%; and of transverse sound speed, 3%. These ranges are probably wider than necessary for electrical-grade copper, but it is instructive to consider the broader ranges specified by generic copper. The extreme parameter values are shown in Table 2. The effects of these are seen in Fig. 2. In no case does the variation of target strength exceed ± 0.1 dB. We have also considered a ± 0.1 mm variation of the sphere diameter. The effect of this on the target strength is negligible, less than ±0.02 dB.

Table 2. Ranges of variation in material parameters of the two spheres. MKS Units.

Parameter	Variation (%)	Copper		WC6%Co	
		Minimum	Maximum	Minimum	Maximum
ρ_1	±1	8858	9036	14751	15049
c_1	±5	4522	4998	6521	7207
c_2	±3	2220	2357	4036	4287

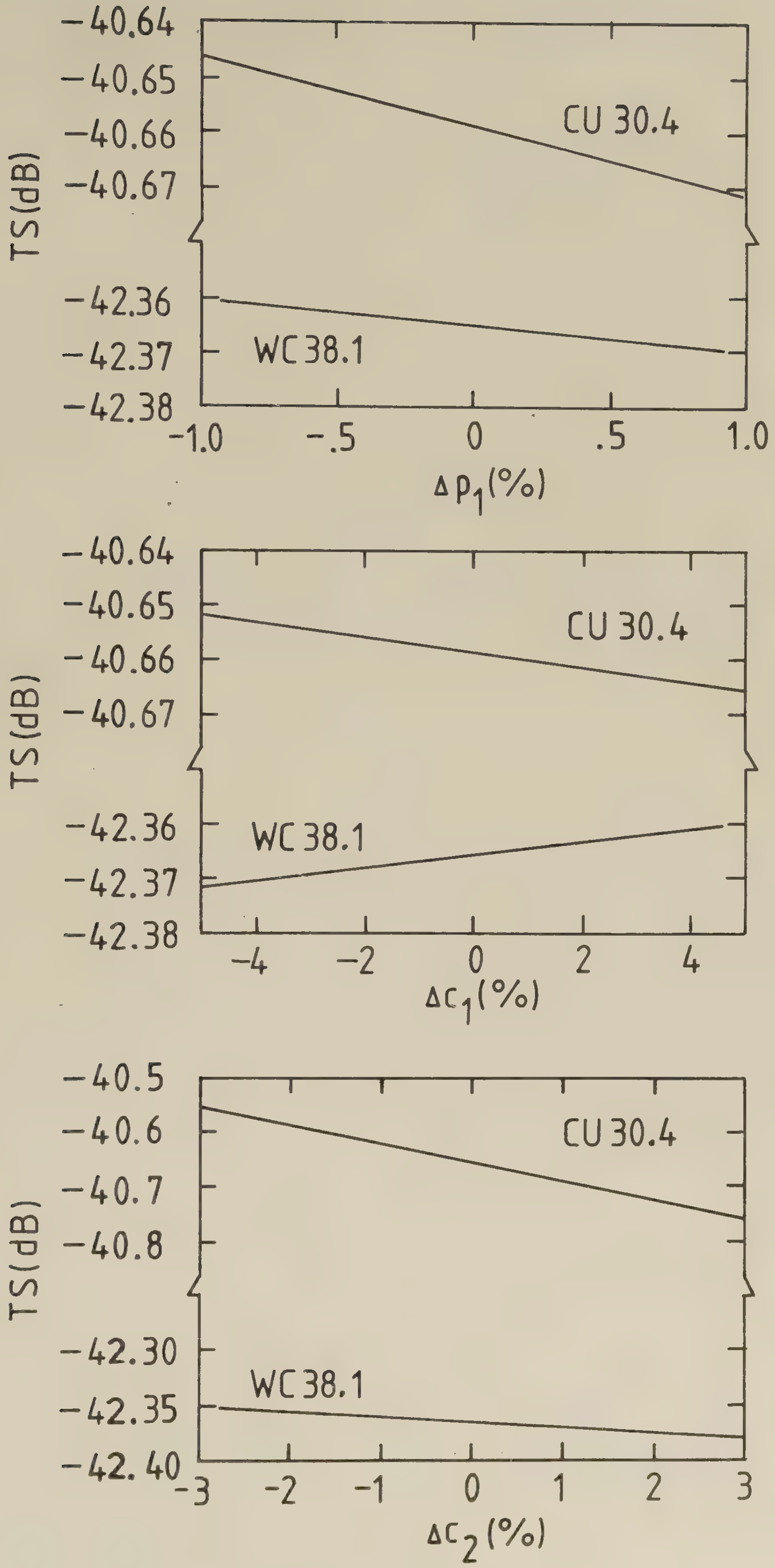

Fig. 2. Effects of variations in material parameters on the target strengths of two calibration spheres.

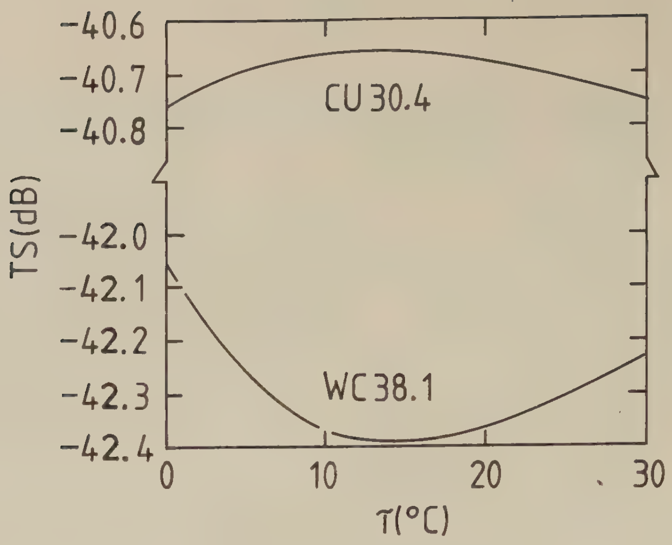

Fig. 3. Effects of temperature variation on the target strength of two calibration spheres, assuming a constant salinity of 35 ppt.

Since the two spheres are intended to calibrate 38 kHz echo sounders in the sea, variations in density and sound speed are treated consistently by assuming causative variations in temperature with a constant salinity of 35 ppt. The relations of Dietrich (1952) and Del Grosso (1974) allow the translation of temperature variations to those of ρ and c. This is done for the temperature range 0 to 30°C in Fig. 3.

The variations in Fig. 3 are larger than those in Fig. 2. This reflects the greater influence of temperature on the target strengths of the calibration spheres. In the case of the copper sphere, the variation about the nominal value, -40.7 dB, does not exceed ±0.1 dB over the entire temperature range. In the case of the tungsten carbide sphere, the variation is within ±0.2 dB, taking the reference value as -42.2 dB which is 0.2 dB higher than the nominal value computed for the conditions of Table 1. However, the reference value -42.3 dB will guarantee a precision calibration from 4 to 30°C, as the change in target strength with temperature is greatest below 4°C. For either sphere, since the hydrography is generally known during a calibration, the absolute value of target strength can be adjusted if required, thus ensuring a theoretical accuracy better than 0.1 dB over the full 30°C range.

Two equipment parameters have been considered: the centre frequency f and duration T of the transmit pulse. T may be varied deliberately during a cruise. f can drift, especially with older equipment. We have calculated the effect of varying f by ±1% and T by ±0.5 ms. The consequent variations of the sphere target strengths are negligible, less than ±0.05 dB.

6. CONCLUSIONS

Copper and tungsten carbide spheres have been produced for the calibration of 38 kHz echo sounders when a target strength of the order of -41.5 dB is required. The 30.4 mm diameter copper sphere has a nominal target strength of -40.7 dB. It is insensitive to temperature changes since the diameter has been optimised. The tungsten carbide sphere is a standard 38.1 mm diameter ball bearing made of sintered tungsten carbide with 6% cobalt binder. Its nominal target strength is -42.4 dB.

The variations considered in the material, medium, and equipment parameters are large enough to cover any that are likely to arise in practice. The corresponding variations of the target strengths of the subject spheres are minor, for the most part not exceeding ±0.1 dB. In the worst case, that of temperature variation on the tungsten carbide sphere, especially below 4°C, the target strength may be corrected if necessary. Indeed, the computed target strength of suitably designed calibration spheres can be adjusted to take account of divergent conditions, thus permitting a potential calibration accuracy better than 0.1 dB. The calibration of hydroacoustic equipment for acoustic surveys should be performed with sufficient care to achieve this accuracy, thus ensuring that the calibration will contribute negligible error to the survey results.

A PROCEDURE FOR CALIBRATING ACOUSTIC SURVEY SYSTEMS, WITH ESTIMATES OF OBTAINABLE PRECISION AND ACCURACY

by

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ABSTRACT

Acoustic survey systems may be calibrated either directly by measuring the received echo intensity from a known weight of caged fish, or indirectly from separate measurements of fish target strength and the acoustical parameters of the echosounder (e.g. transmitted source level, SL, and the transducer receiving sensitivity, SRT). These parameters have previously been estimated from measurements made with hydrophones, which suffer from poor calibration stability, or 'standard targets', whose performance was not adequately characterised. Whilst considerable improvements in standard target design have recently been reported, another calibration technique exists which does not require the use of either calibrated hydrophones or targets. This is similar to the reciprocity technique frequently used to calibrate hydrophones and only requires measurements of ranges and received voltages in order to compute the lumped parameter SL + SRT.

This paper describes such a procedure which has been in use at the Fisheries Laboratory, Lowestoft for the past two years.

RESUME

Les systèmes de reconnaissance acoustique peuvent être étalonnés soit directement en mesurant l'intensité de l'écho transmis par un poids connu de poissons encagés, soit indirectement à partir de mesures séparées de force de cible de poissons et des paramètres acoustiques du sondeur (par exemple le niveau émis par la source, SL, et la sensibilité de réception du transducteur, SRT). Ces paramètres ont été auparavant estimés à partir de mesures effectuées sur des hydrophones, présentant une faible stabilité d'étalonnage, ou sur des 'cibles standard' dont les performances n'ont pas été caractérisées de manière adéquate. Bien que des améliorations considérables dans la conception des cibles standard aient été récemment rapportées, il existe une autre procédure d'étalonnage ne nécessitant l'utilisation ni d'hydrophones étalonnés ni de cibles. Cette procédure, analogue à la technique de réciprocité fréquemment utilisée pour l'étalonnage des hydrophones, exige uniquement la mesure des portées et des tensions reçues pour calculer le paramètre bloqué SL + SRT.

Cet article décrit une procédure de ce type utilisée depuis deux ans au Laboratoire des pêcheries de Lowestoft.

1. INTRODUCTION

The possession of an accurate, repeatable calibration technique is fundamental to the use of acoustic surveys for the estimation of a fish stock size. As a basic minimum, the chosen technique should be capable of providing calibrations precise to ±0.5 dB, although for comparison of results between different laboratories it is necessary to ensure that the absolute accuracy of the calibration also meets this specification.

There are three major calibration methods:

1. The use of 'calibrated' hydrophones and projectors.

Such devices are rarely, if ever, specified to an accuracy better than ±1 dB and this figure can only be relied upon for a short period after leaving the factory. Hydrophones in particular are prone to large, occasionally irreversible, sensitivity changes if subject to shock or temperature variations. These devices cannot, therefore, be relied upon for accurate calibrations.

2. The use of 'standard' targets.

In the past a wide range of inadequately characterised targets have been used with extremely variable results, viz: table tennis balls, trawl floats and numerous metal spheres. Recently, however, the theory appropriate to the use of solid metal spheres has been rationalised and satisfactory standard targets are now available (Foote and MacLennan, 1982). In order to realise the potential accuracy of this technique, considerable care must be taken over the positioning of the target on the acoustic axis of the survey transducer.

3. The use of 'reciprocity' techniques.

A variety of techniques are available in which uncalibrated hydrophones and projectors can be used to calibrate a transducer. This paper describes one such technique which does not rely upon the possession of a reciprocal test hydrophone.

2. THE CALIBRATION TECHNIQUE

The arrangement used to calibrate the MAFF 30 kHz survey system (using facilities generously provided by the UK Ministry of Defence) is shown in Fig. 1. The survey transducer, a projector and a hydrophone are mounted upon suitably distanced stations which could be independently rotated at any required depth. To reduce the possibility of error all the principal components of the acoustic survey system are included in the calibration; not merely the transducer.

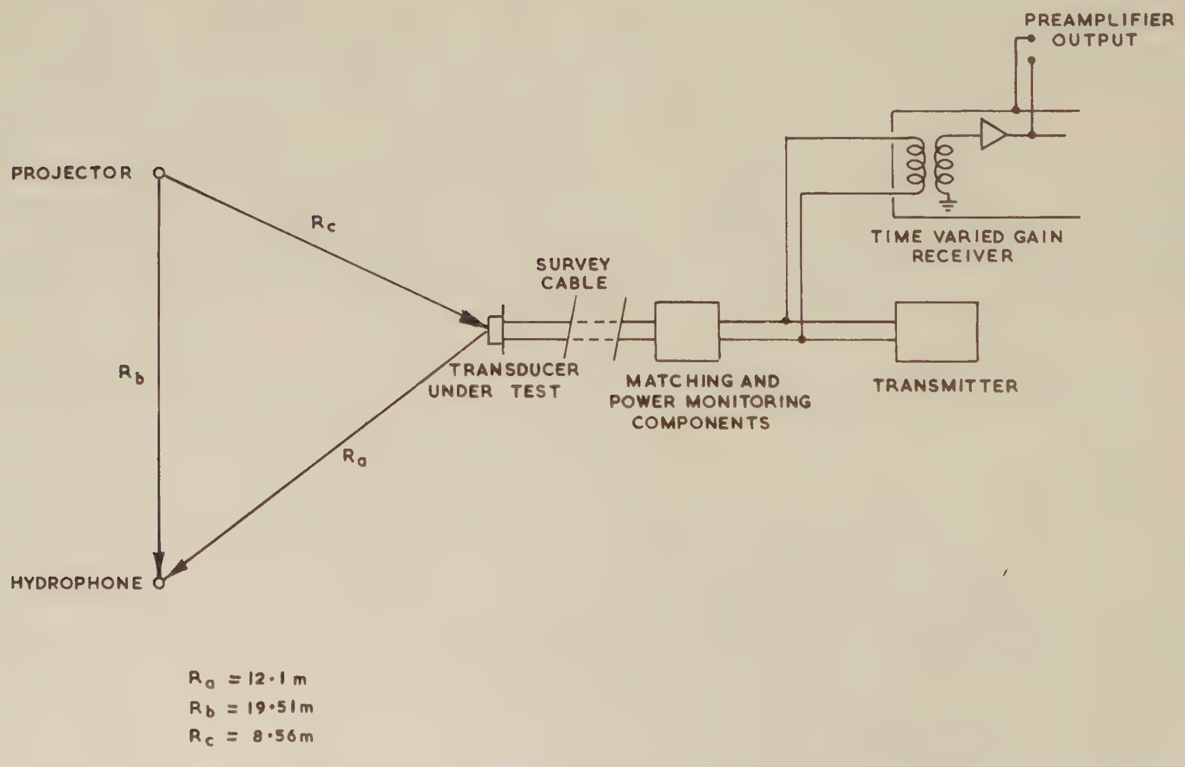

Fig. 1. The calibration arrangement.

The detailed calibration procedure is as follows:

1. First the survey transducer and then the transducer plus cable are tuned to be resistive at the desired operating frequency. The transmitter is then energised and the electrical power into both the cable plus transducer and the transducer alone are measured, from which the cable loss is computed.

2. Whilst the survey transducer is transmitting it is aligned with the test hydrophone and the received voltage at the hydrophone Va volts rms (root mean squared), is measured. It must be emphasised that the true rms voltage of the received waveform should be measured; not the peak or some arbitrary mean value.

3. Power is then applied to the test projector which is initially aligned with the hydrophone and then with the survey transducer. The received rms voltages, Vb and Vc respectively, are measured. From these measurements the following equations are derived:

(a) $SL + Srth - (20 \log_{10} Ra + 2\alpha\, Ra) = 20 \log_{10} Va$

(b) $S_{\ell p} + Srth - (20 \log_{10} Rb + 2\alpha\, Rb) = 20 \log_{10} Vb$

(c) $S_{\ell p} + SRT - (20 \log_{10} Rc + 2\alpha\, Rc) = 20 \log_{10} Vc$

where $S_{\ell p}$ and SL are the projector and survey transducer source levels, Srth and SRT are the receiving sensitivities of the hydrophone, and the survey transducer respectively, α is the acoustic attenuation in dB/metres, and Ra, Rb, Rc are the respective ranges in metres.

By simple algebra, it follows that:

$$SL + SRT = 20 \log_{10} \left(\frac{Va\ Vc}{Vb}\right) + 20 \log_{10} \left(\frac{Ra\ Rc}{Rb}\right) + 2\alpha\ (Ra+Rc-Rb).$$

The parameter SL + SRT is that due to a particular electrical power input to the transducer. For convenience SL + SRT is scaled to an equivalent figure per kilowatt of input power, from which the appropriate value during any later acoustic survey is calculated. Since the electrical power into a particular transducer has been found to vary by less than ±5% during a year (some of which is attributable to measurement error) the possible errors introduced by the assumption of transducer linearity are small.

3. RESULTS

The results from three different experiments with the same 30 kHz transducer and 540 metre length of survey cable are as follows:

SL + SRT	DATE
39.8 dB/kW	June 1980
40.2 " "	June 1980
39.6 " "	October 1981.

Potentially, errors could have been introduced into these data by misalignment of the receiving and transmitting transducers, non-uniformities in the hydrophone's horizontal beam pattern or by inaccurate measurement of either the electrical power into the survey transducer or of the received voltages Va, Vb, Vc. The hydrophone beam pattern was carefully plotted before each experiment and the observed non-uniformities were compensated for by appropriate alignment of the hydrophone during each measurement. The remaining problems due to inaccuracies of alignment and instrumentation were considered unlikely to produce an overall measurement uncertainty of greater than ±0.5 dB. This conclusion would appear to be justified by the consistency of the calibration results, which were obtained from quite different experimental conditions (e.g. different hydrophones, operational ranges and test equipment).

Prior to 1980, the 30 kHz survey transducer was calibrated by means of table tennis balls, which at the time were thought to be satisfactory standard targets. Dunn (1982), has recently performed a detailed investigation into the target strength of these balls and if his data are applied to the results of MAFF calibrations in 1979, the parameter SL + SRT was 39.3 and 39.7 dB/kg respectively. These figures are in good agreement with later data and serve to demonstrate the long-term stability of the MAFF acoustic survey system.

4. CONCLUSIONS

A calibration technique employing uncalibrated hydrophones and projectors has been developed which is capable of producing repeatable calibration accuracies of ±0.5 dB. Further enhancements in accuracy were introduced for the 1982 series of calibrations by the replacement of the MAFF 30 kHz magnetostrictive transducers by more stable multi-element ceramic devices and by the introduction of automated digital instrumentation. The results so obtained have been compared with those derived from calibrations using standard targets similar to those described by Foote and MacLennan, 1982. Agreement was of the order of ±0.25 dB. Use of such targets during an acoustic survey would obviate the need of assuming transducer stability between calibrations and eventually may permit a much more simple calibration technique to be used than that described in this paper.

ACKNOWLEDGEMENTS

The technique described in this paper necessarily includes the work of several of our present and former colleagues at the Fisheries Laboratory, Lowestoft, in particular W.L. Huggins and H.R. Stewardson. This work would also not have been possible without the generous loan of calibration facilities by the Admiralty Underwater Weapons Establishment.

ACOUSTIC BACKSCATTERING CROSS SECTION OF COD AVERAGED BY SIZES AND INCLINATION OF FISH

by

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ABSTRACT

Experimental investigations and plotting of polar diagrams of backscattering of fish from the dorsal aspect were carried out at a lake with the DDR equipment complex. Cod between 20-38 cm long were observed in a special support-rotation system.

Echoes were recorded simultaneously with the rotation of the fish. Polar diagrams were obtained from fish in three length groups: 21-22 cm, 31-32 cm and 35-36 cm.

Patterns from fish in the same size group were normalized. To find the average acoustic cross section, a truncated Gaussian distribution of the tilt angle of a swimming fish was used.

An example shows how the averaged cross section of a fish at a given tilt angle was determined on the basis of the known regressive function σ_{Max} (L) and the normalized target strength value. The refinement of the probability function of tilt angles under natural conditions will improve the accuracy of average target strength estimates.

RESUME

Les études expérimentales et la construction de diagrammes polaires sur le volume de rétro-diffusion du poisson sous l'aspect dorsal ont été conduites dans un lac à l'aide du complexe d'équipement DDR. Des morues entre 20 et 38 cm de longueur ont été observées après avoir été mises dans un système d'entretien et de rotation spécial.

Les échos ont été enregistrés simultanément au roulement du poisson. Des diagrammes polaires ont été obtenus de poissons classés en trois groupes de longueurs: 21-22 cm, 31-32 cm, 35-36 cm.

Les dessins des poissons du même groupe de taille étaient normalisés. Pour trouver la section croisée acoustique moyenne, on emploie une distribution Gaussienne tronquée de l'angle d'inclinaison d'un poisson nageant.

Un exemple démontre comment cette section croisée moyenne d'un poisson à un angle d'inclinaison connu est déterminée à base de la fonction régressive σ_{Max} (L) et la valeur de l'index de réflexion normalisée. Le raffinement de la fonction de la probabilité des angles d'inclinaison sous conditions naturelles servira à améliorer la précision des estimats de l'index de réflexion d'une cible moyenne.

1. INTRODUCTION

Hydroacoustic data are collected from fish schools during stocks assessment surveys by echo integrating systems. In this connection one of the most important factors is the determination of the target strength of an individual fish. Regressions of target strength depending on fish length available in the references (Midttun and Hoff, 1962; Yudanov et al., 1966; Shibata, 1970; Nakken and Olsen, 1973; Dalen et al., 1976) do not always satisfy the investigators since they are obtained for separate fish species and do not consider the biological state of specimens and their behaviour under actual living conditions.

Therefore it is of interest to calculate the averaged target strength both for fish groups of the same and different sizes using polar diagrams of backscattering.

2. EQUIPMENT AND METHODS OF EXPERIMENT

The averaged characteristics of cod backscattering were obtained with equipment system designed specially for these purposes by Institut für Hochseefischerei (Rostock, DDR). The equipment operation is based on a continuous automatic recording of echoes. According to a block diagram (Fig. 1) the target strength of fish is determined by the expression:

$$TS = 20 \lg \frac{U_{omp}}{U_{nag}} + 20 \lg \left(\frac{r_3 \cdot r_2}{r_1 \cdot r_4} \right) \qquad (1)$$

where U_{omp}, U_{nag} are the voltages of the received and transmitted fields;

θ_i is the angle of fish rotation;

r_1, r_2 are the distances from source level to hydrophone and fish respectively;
r_3 is the distance from fish to hydrophone;
r_4=1m

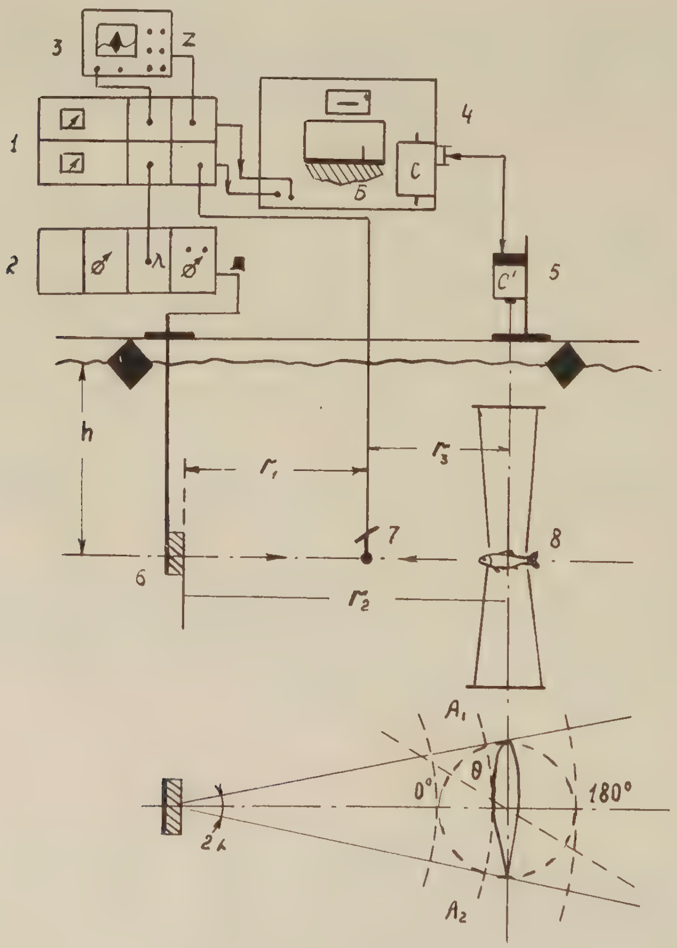

Fig. 1. Block diagram of the equipment. 1- two-channel amplifier 2- generator, 3- oscilloscope, 4- recorder, 5- fish support-rotation system, 6- transducer, 7- hydrophone, 8- fish, A_1-A_2- wave front.

In 1979/1980 the polar diagrams of backscattering of cod with length range of 20-38 cm were obtained in the dorsal and side aspects. The support-rotation system permitted to rotate the fish with an accuracy of 1°. The MS-29 transducer of echo sounder served as a pulsed source (frequency 30 kHz, pulse length 0.5 msec.) and the hydrophone - as a receiver of echoes. Variation of direct field pressure in the zone of fish habitat did not exceed 5%; variation of hydrophone response (IC-32) (frequency 30 kHz) made up 0.8 db by the intensity in forward and reverse directions.

The echoes received by the hydrophone arrived after strobing at a peak detector and then they were transmitted in the analog form to a PSG-101 recorder; the accuracy of graphic plotting was 0.5 db. Before the acoustic measurements the measuring system was calibrated using a standard target which was a ping-pong ball. The equipment was considered to be ready for operation if the variation of the backscattering field of the standard target did not exceed ±1db.

The polar diagrams of backscattering of 20 fishes showed that echoes varied within a wide range depending on the angle of rotation.

The average acoustic backscattering cross section of fish at sector $\Delta\theta$ (dorsal aspect) was defined:

$$\bar{\sigma}_L\ (\Delta\theta) = \Sigma\bar{\sigma}(\theta_i) \cdot w(\theta_i) \qquad (2)$$

where $\bar{\sigma}(\theta)$ is the ensemble-averaged function of backscattering cross section of a fish;

$\omega(\theta)$ is the probability density function of tilt angle;

θ_i is the inclination of the long axis of fish relative to the horizontal plane.

For fish of the same size ($\Delta L<\frac{\lambda}{2}$; where ΔL is the deviation in length from the mean length in the group, λ is the wave length) the function $\bar{\sigma}(\theta)$ is found through averaging a number of backscattering patterns of individual specimens:

$$\bar{\sigma}(\theta_i) = \frac{1}{n}\sum_{j=1}^{n} \sigma_j(\theta_i) \qquad (3)$$

where $\sigma_j(\theta_i)$ is the acoustic cross section of j-fish

n is the number of fish patterns in averaging.

The function $\omega(\theta_i)$ characterizes the behaviour of fish in natural conditions of their habitat. If, during the swimming, the fish body inclination varies within $\pm\Delta\theta$ and is described by a truncated Gaussian distribution with parameters $\bar{\theta}=0^{\circ}$ and $S_\theta = 1/3\ \Delta\theta$ ($\bar{\theta}$ is the average tilt angle, S_θ is the standard deviation), the expression (2) will be:

$$\bar{\sigma}_L(\Delta\theta) = \frac{1}{n}\sum_{j=1}^{n} \sigma_j(\theta_i) \cdot [F_o(h_2)-F_o(h_1)] \qquad (4)$$

where F_o is the Laplacian-Gaussian integral;

$$h_1 = \frac{\theta_H-\bar{\theta}}{S_\theta}\ ; \qquad h_2 = \frac{\theta_b-\bar{\theta}}{S_\theta} \qquad (5)$$

where θ_H, θ_b is the low and high limit of the interval $\Delta\theta$.

3. RESULTS

Average acoustic backscattering cross sections of cod with length range of 21-22 cm (4 specimens), 31-32 cm (5 specimens) and 35-36 cm (6 specimens) were calculated for the dorsal aspect using the expression (4). For averaging by the expression (3) the

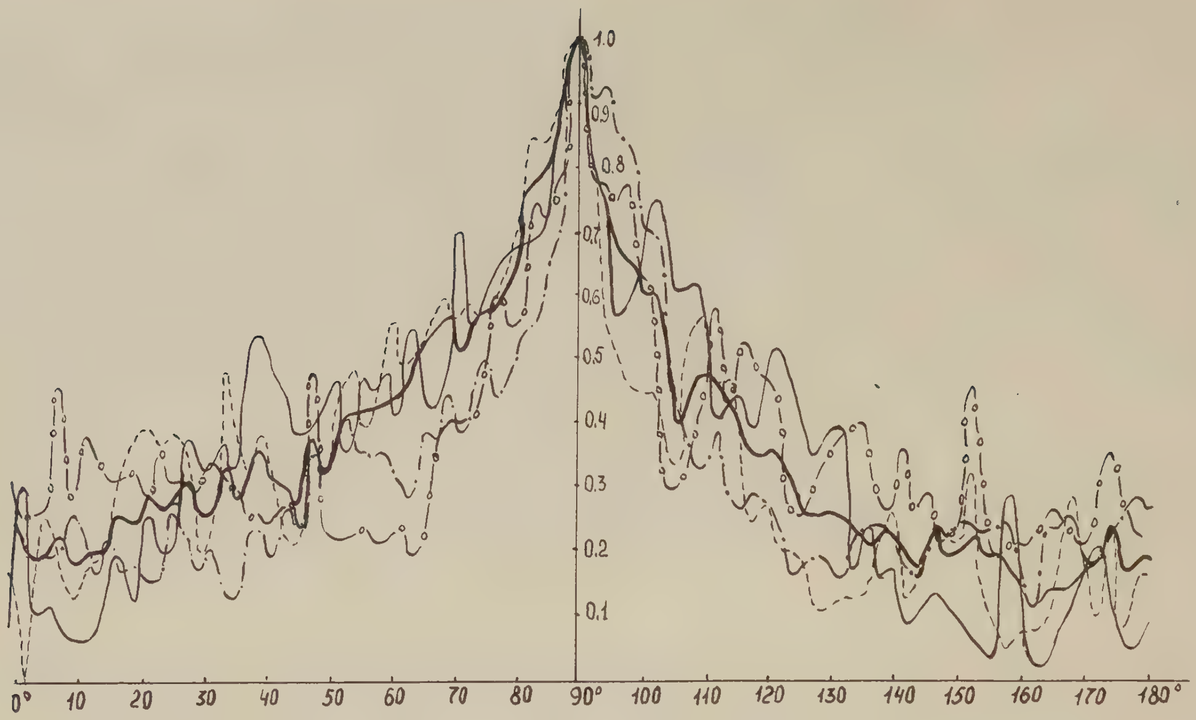

Fig. 2. Characteristics of backscattering of cod with length range of 21-23 cm and averaged pattern; ——— 21 cm, —•— 21.5 cm, — o — 22.5 cm, — — — 22.7 cm, — average.

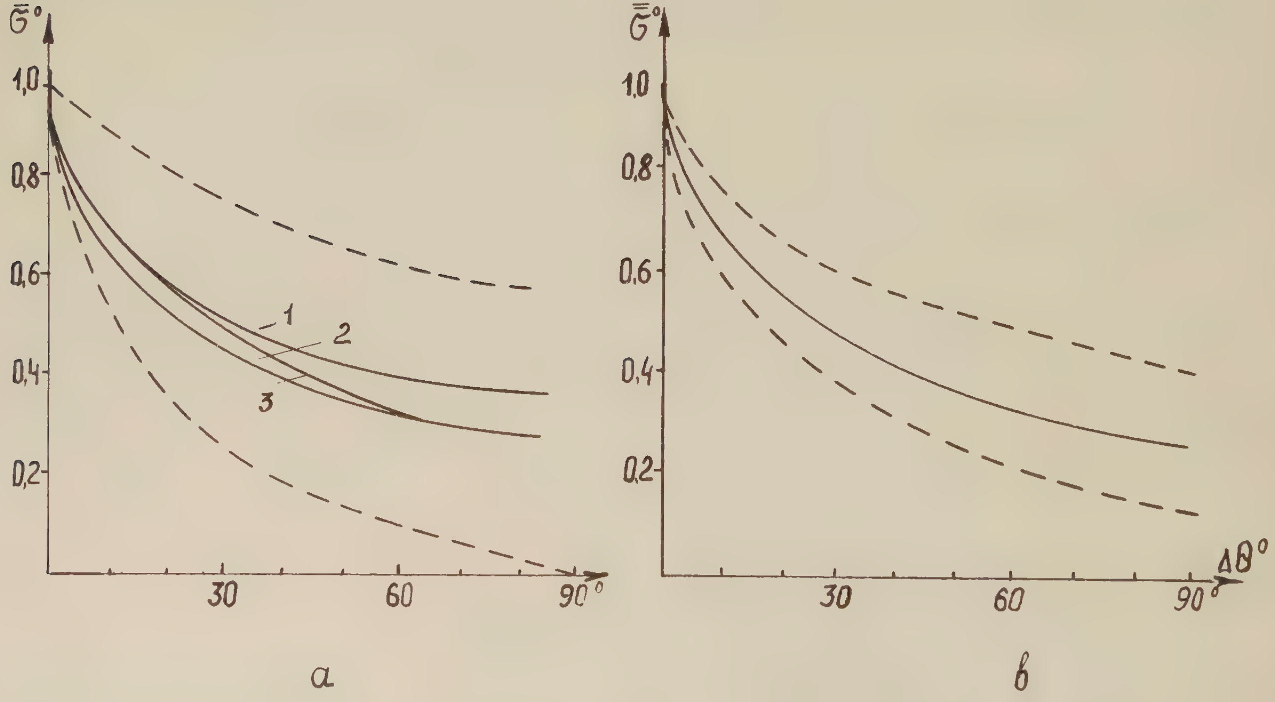

Fig. 3 (a) Normalized functions of the acoustic cross section for three groups of cod depending on the value of angle of averaging
(b) Normalized function of average acoustic cross section for groups of fish with length range of 21-36 cm depending on the value of angle of averaging, Δθ.

normalization of all values relative to their maximum was first made. Fig. 2 presents the normalized diagrams of backscattering of individual fishes 21-23 cm long and averaged diagrams. The comparison of the results (Fig. 3a) showed similarity in function $\bar{\sigma}^o_L$ for three cod groups depending on the value of angle of averaging. It indicated the existence of a common mean the value of which is defined through averaging of normalized group functions:

$$\bar{\bar{\sigma}}^o(\Delta\theta) = \sum_{L=1}^{K} \bar{\sigma}^o_L(\Delta\theta) \qquad (6)$$

where K is the number of length groups.

Fig. 3b shows averaged normalized backscattering cross section $\bar{\bar{\sigma}}^o$ and its standard deviation depending on the value of angle of averaging, ±Δθ.

Using the function $\bar{\bar{\sigma}}^o(\Delta\theta)$, let us find the average acoustic cross section of cod with length range of 21-36 cm:

$$\bar{\bar{\sigma}}(\Delta\theta) = \sigma_{max} \cdot \bar{\sigma}^o(\pm\Delta\theta) \qquad (7)$$

where σ_{max} is the maximum acoustic cross section (Yudanov *et al.*, 1966; Gankov, 1980).

As an example we find average acoustic cross section of cod at $\Delta\theta=\pm20^o$. At frequency 30 kHz the expression for calculating the maximum acoustic cross section will be (Yudanov *et al.*, 1966):

$$\sigma_{max} = 0.003\ \bar{L}^{2.93} \qquad (8)$$

where L is the mean length of cod in the group.
The average normalized acoustic cross section at $\pm20^o$ is found (Fig. 3b):

$$\bar{\bar{\sigma}}_{\pm20} = 0.55 \pm t \cdot 0.11 \qquad (9)$$

where t is the Student's coefficient.

The results of calculations using the expressions (7, 8, 9) are presented in Table 1, where S_L is the standard deviation of mean length.

Table 1. Average acoustic backscattering cross section of cod

Nos	$\bar{L}$ (cm)	S_L (cm^2)	σ_{max} (cm^2)	$\bar{\bar{\sigma}}^o_{\pm20}$ (cm^2)	95% confidence interval
1	22	0.8	25	14	8-20
2	32	1.0	75	42	25-59
3	36	0.4	105	58	35-81
Σ	30	6.0	64	35	21-49

The proposed method of treatment and presentation of results opens the way for practical use of reported data on maximum target strength of fishes. The polar diagrams of backscattering (Haslett, 1973; Shatoba and Fedotova, 1981) in dorsal and side aspects make it possible to calculate approximate values of the *in situ* target strength.

Observations using underwater photo- and television equipment will permit to refine the probability density function of tilt and rotation angles of swimming fishes and to reduce the error in the estimate of average acoustic cross section.

List of symbols and units

TS - target strength, dB

σ_{max} - maximum acoustic cross section, cm^2

$\bar{\sigma}(\theta)$ - ensemble-averaged function of backscattering cross section of fish of the same size

$\bar{\sigma}^{o}_{L}(\Delta\theta)$ - normalized function of average acoustic cross section for groups of fish of the same size depending on the value of angle of averaging

$\bar{\bar{\sigma}}^{o}(\Delta\theta)$ - normalized function of average acoustic cross section for a group of fish of different size depending on the value of angle of averaging

r - distance, m

U_r - echo signal voltage, v

U_{tr} - transmitted voltage, v

θ - tilt angle, degree

$\Delta\theta$ - interval, d

θ_l - low limit of the interval

θ_h - high limit of the interval

$\bar{\theta}$ - average tilt angle

S_θ -standard deviation of average tilt angle

L - fish length, cm

$\bar{L}$ - mean length of fish in the group

S_L - standard deviation of mean length

K - number of length groups

n - number of fish of the same size in the group

$F(h)$ - Laplacian-Gaussian integral

$\omega(\theta)$ - probability density function of tilt angle of fish

λ - wave length, cm

t - Student's coefficient

MEASUREMENT OF THE TARGET STRENGTH OF LIVE HERRING AND MACKEREL

by

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ABSTRACT

This paper describes measurements of the target strength of live free swimming but caged pelagic fish at 38 kHz. The measurements were made between 1978 and 1981 at the Marine Laboratory's field station at Loch Duich on the west coast of Scotland. It includes a detailed description of the methods of capture, transport and handling of pelagic fish, and describes the experimental apparatus and various experiments designed to investigate the target strength per kilo and its variation with time, depth and species.

The paper includes a discussion on the probable sources of error within the experiment, the validity of measurements and their possible application in acoustic surveys.

RESUME

Dans ce travail, les auteurs décrivent des expériences effectuées entre 1978 et 1981 sur la mesure de l'index de réflexion à 38 KHz de deux espèces de poissons pélagiques encagés dans les eaux de Loch Duich sur la cote ouest de l'Ecosse. La méthode de capture, de transport et de manipulation des poissons ainsi que le dispositif expérimental sont décrits et discutés. Les valeurs de l'index de réflexion par kilo et leur variation en relation au temps et à la profondeur sont considérées.

Les sources d'erreur dans cette expérience ainsi que la validité des résultats et leur application à des campagnes acoustiques sont discutées.

1. INTRODUCTION

If accurate estimates of fish stocks are to be made with acoustic techniques, then a precise knowledge of the target strength of species present in the water column is required. Several methods of measuring target strength have been reported, eg., *in situ* methods (Robinson, 1982; Traynor and Ehrenburg, 1981); measurements of dead or stunned fish (Nakken and Olsen) and measurements of live, caged fish (Johannesson and Losse); Edwards, 1975; Forbes, Simmonds and Edwards, 1982). This paper describes seven experiments on live, caged herring (*Clupea harengus*) and three on live caged mackerel (*Scomber scombrus*). The experiments were designed to investigate the nature of target strength and the way in which it varies with time, depth, temperature, salinity, tidal cycle and light levels. These experiments are part of a series which started in 1979 (Edwards, 1980) and continued in 1980 (Edwards and Armstrong, 1981) and 1981.

2. MATERIAL AND METHODS

2.1 Material

2.1.1 Experimental Rig and Electronics

The experimental technique was similar to that devised by Edwards (1975) and refined by Dunn (1979) and Forbes, Simmonds and Edwards (1982). The fish were contained in an experimental cage which was surrounded by a guard cage. The guard cage was hung from a transducer platform, which was in turn suspended from a raft moored in Loch Duich in approximately 90 m of water 600 m from the shore.

The electronic equipment was housed in a portable laboratory on the shore. All the connections from the raft and the experimental rig below it to the Laboratory were made through 1 km of cable.

Detailed descriptions of the electronic systems are to be found in Dunn (1979) and Forbes et al. (1982). These systems provide a summary of the acoustic information in a six minute cycle. Each summary contains information from 1,000 sound transmissions which are recorded on magnetic tape. It is from these summaries that the results presented here were calculated.

Diagrams depicting the general layout are presented in Edwards (1980) Figs 1 and 2. However, several modifications were made in 1981 to improve the performance of the experimental technique:

(a) The experimental cage, in which the fish were contained, was constructed from a fine mesh (2 mm bar) PVC coated glass fibre net. (These cages had the same dimensions as those previously used, ie 2 m across the 'flats' and 1 m deep). The new netting was smoother and more visible than previous netting and these two factors combined to reduce injuries caused by fish colliding with the experimental cage, thus reducing mortality. Unfortunately this improvement had an unwanted side effect of increasing the background reverberation. However, this only caused difficulties in the mackerel experiments, where two solutions were devised: In one experiment the density of mackerel in the cage was raised to compensate for the increase in reverberation and in another experiment the guard cage was removed to reduce the overall reverberation of the experimental system.

(b) The range of the experimental rig and the standard reference target were increased by 1 m in order to reduce the errors caused by the near field of the transducer on the standard target. The increase in range reduces the angle subtended by the experimental cage and this alters the equivalent beam angle. A new value of -17.52 dB ref 1 sterad^{-1} has been calculated and used in the analysis.

2.2 Methods

2.2.1 Calibration

The acoustic system is calibrated with reference to a standard sphere positioned on the acoustic axis of the transducer. The standard used was a 69.9 mm brass sphere which was originally measured at -31 dB with reference to a table tennis ball (-42 dB) at a range of 6.5 m (Dunn, 1979). Recent work by MacLennan (1981) in which the brass sphere was recalibrated with reference to theoretical and practical measurements on a tungsten carbide sphere indicate that the target strength of the brass sphere is -32.4 dB. The results presented in this paper are based on these measurements combined with corrections for near field effect and time varied gain error (Simmonds and Forbes, 1982).

2.2.2 Behavioural Monitoring

The fish were continuously monitored with a low light closed circuit TV system which was equipped with a video tape recorder. TV pictures were recorded in 5 min blocks, three times a day, to monitor the distribution, behaviour and condition of the fish.

2.2.3 Fish Capture and Transport

Perhaps the most difficult part of the experimental procedure reported here is the capture and maintenance of live fish in good condition. This is particularly important when the fish are delicate and easily damaged by abrasion, as in the case of herring and mackerel. All transfers of fish from one enclosure to another were carried out with great care using large plastic buckets to ensure that the fish never left the water.

The small herring (9 cm) were captured with a beach seine in Dunstaffnage Bay, near Oban, where they were stored in 4 m x 4 m x 4 m floating enclosures for approximately six weeks prior to being transported by road to the Lock Duich field station (a distance of 30 km). The fish were transported in three one cubic metre tanks with a packing density of approximately 1,300 fish per cubic metre. The water was continuously aerated with compressed air forced through submerged diffusion blocks. At the field station the fish were transferred to a fish carrying barge (Edwards, 1980a) in which they were transported and stored. The overall mortality rate from Dunstoffnage Bay to the experimental rig was very low, less than 0.3%.

The 24 cm herring were captured using a two boat ring netting technique in a similar manner to that previously reported by Edwards (1980a) and Edwards and Armstrong (1981). The fish were transported to the field station in the fish barge and then stored in 4 m x 4 m x 4 m floating enclosures for periods of up to six weeks before use in experiments. Packing densities in the fish barge and floating enclosures were approximately 50 and 10 fish per cubic metre respectively. Mortality rates were variable and depended on the sea state at the time of capture and varied between 1% and 50%.

Mackerel were captured in the vicinity of Kyle Rea from FV 'Snark' using feather jigs with barbless hooks. The mackerel were released directly into the fish barge's tank by inverting the hook and allowing the fish to fall into water. Care was always taken not to handle the fish, since this can result in a loss of scales. Areas where scale loss occurs become clearly visible as dark blue marks and fish marked in this way generally die within 48 hours. Mackerel were transported in the barge which was towed behind the fishing boat to the field station and stored in 4 m x 4 m x 4 m floating keep cages for periods of up to four weeks. The mortality rates from capture to the experimental cage, excluding badly hooked fish which were discarded, was approximately 5%.

2.2.4 Swimbladder volume measurements

Swimbladder volume measurements were made by Mr R. Batty (SMBA Dunstaffnage) on herring using a technique described by Blaxter _et al._ (1979) which consisted of placing a stunned herring in a sealed vessel and subjecting it to a range of pressures above and below atmospheric pressure. The application of Boyle's Law with correction for the compliance of apparatus and the fish with its swimbladder removed allows the calculation of the swimbladder volume.

The swimbladder volumes of groups of 30 fish from controls kept in the floating pens and from similar groups of fish subjected to the experimental procedure were measured to determine if any difference in swimbladder volume existed. The fish removed from the experimental cage were denied access to the surface of the water to prevent them swallowing air and reflating their swimbladders (Blaxter _et al._, 1981) before the swimbladder volume measurements were made.

2.2.5 Environmental Measurements

Throughout the experiments the temperature, salinity and tidal cycle were monitored by an NBA Controls DNW5 (STD) once every six minutes syncronously with acoustic data. The STD recorder was moored at approximately the same depth as the experimental cage but displaced 100 m away from the cage. The STD stored the information on magne tic tape, the data being subsequently decoded by NBA Controls and then combined with acoustic data.

3. RESULTS

3.1 Behaviour Measurements

Nakken and Olsen (1977) have demonstrated that the tilt angle of the fish is an important factor when considering the target strength of fish. Further, the method of integration used in these experiments requires that the fish are uniformly distributed throughout the experimental cage. From observations made with the low light level TV system placed directly below the experimental cage it is impossible to measure the tilt angle of the fish. It is, however, possible to gauge if the fish are behaving 'normally' and it soon becomes obvious if the fish are swimming with tilt angles close to ±90°. With the exception of the initial settling periods, when the fish were very active, no 'abnormal' fish behaviour was noted. A limited analysis of the distribution pattern shows that there is no obvious bias in the area density of fish within the experimental cage.

3.2 Target Strength of Herring

All the measurements of the target strength of herring from the Loch Duich site are summarised in Table 1. The data for previous years have been corrected to take account of the most recent calibration data (MacLennan, 1981) and this takes the form of a reduction of 1.2 dB in the target strength per kilo.

Table 1. Summary of Results: Target Strength of Herring.

Experiment Number	No of Fish	Mean Length (cm)	S.D.of Length (cm)	Total Weight (kg)	Mean Weight (gm)	S.D. Weight (gm)	T.S.pr kilo at 17.5m (dB)	S.D.of T.S. (dB)	T.S.pr kilo at 47.5m (dB)
7/78	111	22.2	1.77	8.52	76.0	20.9	-32.4		
8/79	68	21.7	2.23	5.80	86.6	25.9	-31.4		
9/79	80	24.7	1.64	9.12	114.8	22.3	-33.7		
11/79	116	24.0	2.50	17.34	104.8	29.8	-32.4	0.19	
12/79*	250	23.7	3.03	24.92	99.6	33.7	-33.1		
13/80	109	24.1	1.58	9.89	90.7	17.0	-34.5		
14/80	31	22.9	2.03	2.95	93.2	22.0	-32.5		
15/80*	97	24.0	1.91	9.60	100.0	23.9	-35.5		
16/80	96	23.8	1.73	8.64	91.0	20.9	-35.0		-36.2
17/80	122	24.3	1.60	11.91	99.8	18.0	-35.3		-37.6
10a/81	3017	9.14		11.22	3.72		-26.29	0.82	
10b/81	2405	9.14		10.80	3.72		-24.55	0.72	
11/81	1398	8.94		4.47	3.19		-28.32	0.85	
15/81	98	23.3	3.20	9.11	92.03	22.6	-29.65	1.25	
16/81*	103	23.4	3.50	10.16	97.70	26.4	-31.79	0.44	
18/81	78	24.4	2.78	8.10	103.80	22.9	-39.19	1.35	
19/81	89	25.1	3.40	9.25	103.90	25.0	-33.62	0.54	-33.70
20/81*	35	24.3	4.40	3.84	107.3	27.4	-31.43	0.41	
21/81*	88	25.2	3.3	9.67	108.6	22.8	-33.86	0.39	-31.45

* Data used to calculate the mean target strength at 17.5m

3.2.1 Target strength of 24 cm herring at 17.5 m

The mean target strength obtained for the six experiments conducted in 1981 was -32.4 dB per kilo at 17.5 m. This mean was calculated by assuming that all the experiments are independent estimates of target strength. On the same basis the target strength for all sixteen experiments was -32.9 dB per kilo. If experiments in which mortalities occurred within the first 48 hr are excluded (as suggested in Edwards and Armstrong, 1981), along with experiment 1/79 which used continuous artificial lighting, then the mean target strength at 17.5 m is -33.5 dB per kilo. This is derived from over 624 hr of observation with no mortalities and no escapes.

3.2.2 Target strength of 24 cm herring at 47.5 m

Since the swimbladder in the herring is thought to be the major source of reflected sound, an increase in ambient pressure should reduce the volume of the swimbladder and the quantity of sound reflected. The two experiments reported in 1980 confirmed this hypothesis, with reductions of 2.4 and 3.5 dB respectively from the values obtained at a depth of 17.5 m. In the first experiment, 19/81, a reduction of 2.08 dB was observed. In the second 21/81 an increase of 2.41 dB was observed. The increase took the form of a 5 dB step increase when the fish were lowered (Fig. 2b and c) followed by a decline to its previous value over a period of three days. The reasons for the increase are not understood. As in the previous experiments there was insufficient light to allow the TV system to operate at 47.5 m and so no information on the way in which the fish behaved is available.

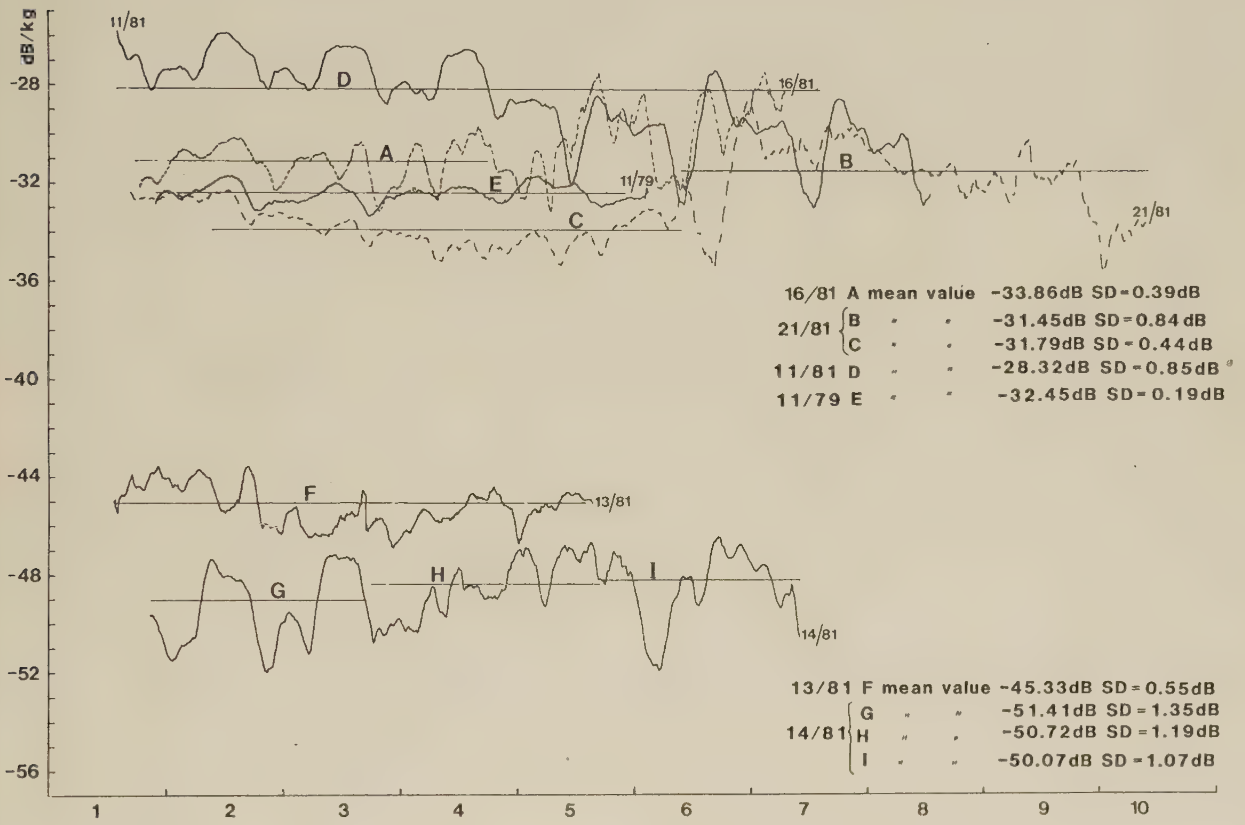

Fig. 1. Target strength of herring and mackerel at various depths.

3.2.3 Target strength of 9 cm herring at 17.5 m

The mean target strength per kilo of 9 cm herring was measured as -26.12 dB. Mortality was very low in the small herring experiments: less than 0.1% in experiment 10/81 and 0% in experiment 11/81. Observations of fish behaviour were made with closed circuit TV system, but the large number of fish used (over 3,000 in experiment 10/81) made it impractical to quantify the distribution of fish in the cage. Qualitative observations suggest that the distribution is sufficiently uniform to avoid significant error.

3.2.4 Length dependence of the target strength of herring

A linear regression was fitted to the three observations on 9 cm herring and the eight valid observations on 24 cm herring. The results are illustrated in Fig. 2. The regression calculated for fish of length L cm was:

Target strength per kilo = $-17.09 \text{ Log}_{10}(L) -10.6$ dB

The correlation coefficient was -0.91 for 11 data points.

3.2.5 The effects of light levels

The target strength on caged herring varied in a cyclic manner within periods close to 24 hrs, being, in general, lower at night by 2 to 3 dB (Figs 1(B) and (C)). The standard deviation of 1 hr means (ie: means calculated from 10,000 sound transmissions) is in the range 0.4 to 1.25 dB, and the range of values observed was approximately 10 dB. In experiment 11/79, (Fig. 1(D)) when artificial light was used throughout the experiment, the standard deviation was 0.19 dB and the range of values was 3.3 dB.

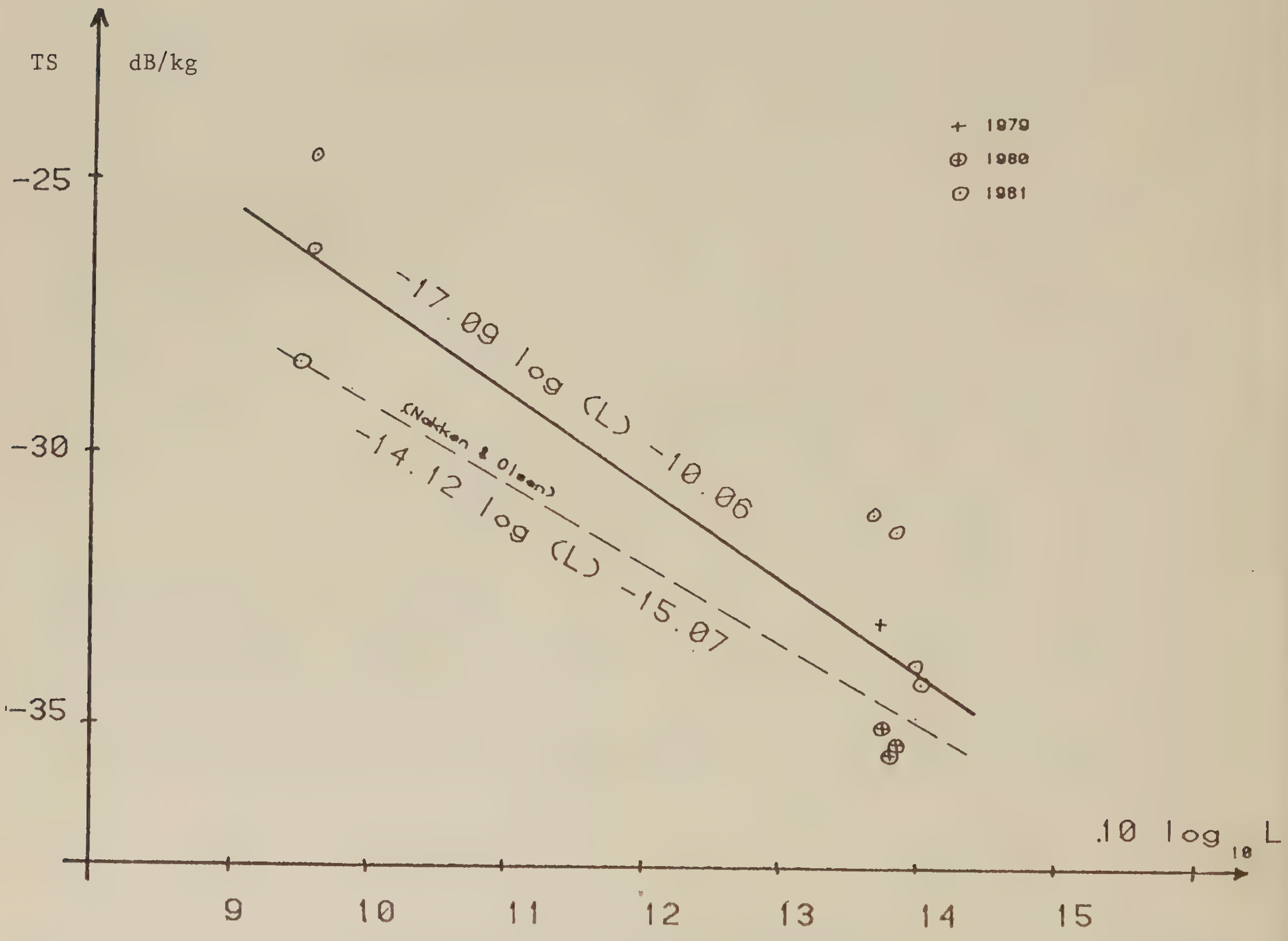

Fig. 2. Length target strength regression for herring.

3.2.6 The effects of temperature and salinity

At 17.5 m the water temperature and salinity were constant over a typical six day experiment to better than 0.1°C and 0.2 ppm respectively, although both absolute values did drift slowly with time.

3.3 Herring swimbladder volume measurements

Measurements were made by R. Batty of SMBA, Oban, to evaluate the swimbladder volume of the 24 cm herring and to investigate any difference which might exist in swimbladder size before and after the experiments. Samples of 30 fish were taken from the experimental rig at the end of the experiment and compared with 30 similar fish sacrificed at the start of the experiment. The swimbladder volume of 25.16 cm herring was calculated at 3.21 ml (R. Batty, pers. comm.) and no significant difference in swimbladder volumes was found between the fish before and after the experiments. However, these measurements did show that herring in poor physical condition, although still actively swimming, had no gas in their swimbladders.

3.4 Target strength of mackerel

Mackerel, unlike clupeoids and gadoids, do not have swimbladders, and so their target strength is expected to be low. Edwards and Armstrong (1981) suggested from tentative measurements, that it was in the range -47 to -50 dB per kilo. In 1981 the experiments to confirm this estimate were performed (Table 2). The first (13/81) used the existing 'high reverberation' cage which was compensated for by increasing the quantity of fish to 73.61 kg, a factor of four higher than the previous maximum. The target strength was measured as -45.33 dB per kilo (Fig. 1F) with a standard deviation for 1 hr mean of 0.55 dB. In the second experiment the outer guard cage was removed, reducing the reverberation level by a factor of four. In this experiment the target strength at 17.5 m were measured as -51.41 and -50.07 dB per kilo with a standard deviation of 1.35 and 1.07 dB respectively (Fig. 1G and 1I).

Table 2. Summary of Results: Targets Strength of Mackerel.

Experiment Number	No of Fish	Mean Length (cm)	S.D.of Length (cm)	Total Weight (kg)	Mean Weight (gm)	S.D. Weight (gm)	T.S.pr kilo at 17.5m (dB)	S.D.of T.S. (dB)	T.S.pr kilo at 47.5m (dB)
12/81	64	32.8	3.6	17.77	277	83.1	-44.59	2.60	
13/81*	249	34.8	3.6	73.61	295	54.5	-43.33	0.55	
14/81*	135	32.9	3.9	37.46	275	63.8	-51.41	1.35	-50.72

* Data used to calculate the mean target strength at 17.5m

The second experiment (14/81) also investigated the variation of target strength with depth, and as might be expected, the target strength of -50.07 dB at 47.5 m (Fig. 1H) (a factor of two in pressure) is not significantly different from that at 17.5 m (Fig. 1G and 1I).

The mean target strength at 17.5 m for the two experiments was -47.38 dB per kilo.

4. DISCUSSION

This discussion is devoted to aspects of the experiments which effect the validity of the result, and in particular their application to acoustic surveys.

The mean target strength of -33.5 dB per kilo for 24 cm herring and -26.12 dB per kilo for 9 cm herring at 17.5 m was calculated for multiplies of 24 hr periods to prevent the data from being biased by the variation within the 24 hr cycle. The data were also screened for anomalies caused by poor weather conditions, and electronic and mechanical malfunctions. Further, only experiments with at least 48 hr of valid data were included, and only the sections of these experiments with no mortalities and escapes were used. Despite these qualifications the scatter of values obtained from the experiments was 3.87 dB and 3.77 dB for 24 cm and 9 cm herring respectively. The reason for this range of values is not understood. However, since the environment in which the experiments were undertaken was either controlled (depth) or monitored (temperature and salinity), with the exception of the ambient light level, the authors can only deduce that the variation was caused by behavioural effects, and that these effects were probably influenced by the light level and the restriction in movement, the experimental cage being 1 m deep and suspended at a constant depth of either 17.5 m or 47.5 m. Credence is lent to this argument by the experience of fishermen and researchers who have observed herring rising from near the bottom at dusk, to the surface and returning to the depths at dawn. Further, the phase of the moon and the extent of cloud over are also known to influence the behaviour of herring shoals.

The ambient light levels at the experimental cage are not consistent. Observations from the TV monitoring system indicate that the light levels are controlled indirectly by fresh water run-off from the neighbouring mountains, which contains a high density of particles in suspension.

Investigations by Blaxter *et al.* (1979) have shown that herring cannot actively absorb or secret gas from their swimbladders, but it slowly diffuses through the swimbladder wall into the tissue. Thus the volume of gas in the bladder will slowly decrease with time if the fish are denied access to the surface. The measurements by Mr. R. Batty did not show a significant difference in swimbladder volume between herring kept at the surface and these maintained at depth, nor is there any general tendency for the target strength to decrease with time. However, the duration of the experiments was short by comparison with the maximum time a herring can survive without access to the surface (Blaxter, 1979).

The effects of an increase in pressure on caged herring are important in the context of the daily migration observed in the sea. The experiments designed to investigate this gave conflicting results. Three resulted in an expected decrease of 2 to 3 dB while the fourth produced an unexpected rise of 5 dB followed by a slow fall to the mean value at 17.5 m over a period of three days. The anomolous experiment used fish which had been kept in floating pens for six weeks, at least three weeks longer than the previous storage time. It also took place in late November and early December during a period of heavy rainfall which reduced light from the very short day still further. These factors may make the results from this experiment unrepresentative.

Fig. 2 includes a comparison of the target strength per kilo regression with one derived from Nakken and Olsen (1977), by deducting 6 dB per individual from their maximum dorsal aspect target strength and converting this target strength per kilo, using length and weight data supplied by Mr. J.A. Morrison (pers. comm.). The Nakken and Olsen regression is not quite linear in logs when transposed to target strength per kilo. However, if it is assumed to be linear for the range 10 cm to 25 cm than the equation of the line is:

$$TS_{kg} = -14.12 \text{ Log}_{10}(L) -15.07 \text{ dB per kilo}$$

which compares favourably with, and is within the range of, values measured on live caged fish.

The measurements of the target strength of mackerel give results in the range -45.33 to -51.41 dB with a mean of -47.38 dB per kilo. The experiment which investigated the effects of an increase in pressure showed the expected result of no effect. The experiment which used a very high packing density to compensate for a high reverberation level also had a very low standard deviation, presumably because the high density of fish restricted the range of possible tilt angles. Thus one would expect the mean target strength to be higher than in the experiment with a low density of fish.

It is clear that the application of these results to acoustic surveys must proceed with caution. The fish are constrained in an 'unnatural' environment and this will affect their behaviour. The collection of data from a controlled and monitored environment is leading to a better understanding of the nature of target strength and the factors which cause it to vary. When these and future measurements are combined with data from *in situ* measurements it should be possible to construct a table of target strength values which will improve the precision of acoustic surveys.

5. CONCLUSIONS

The mean target strength of herring at 17.5 m is -33.5 dB for 24 cm fish and -26.12 dB for 9 cm fish.

The target strength per kilo against length regression for herring is $-17.09 \log_{10}(L) -10.6$ dB where L is the fish length in cm.

The target strength of 33 cm mackerel at 17.5 m and 47.5 m is -47.38 dB and no significant variation with depth was observed.

ACKNOWLEDGEMENTS

The authors would like to thank the crews of FRV "Goldseeker", FV "Santa Maria II", FV "Santa Maria III", FV "Regina Maris" and FV "Snark" for their assistance in the capture of live fish, and Dr J.H.S. Blaxter and Mr R. Batty of SMBA, Oban, for supplying 9 cm herring and measuring herring swimbladder volumes. Thanks also to Mr R.G.G Lawrie, Mr I.B. Petrie and Mr P.J. Copland for their assistance throughout the project, and to Mr E.J. Simmonds and Mr S.T. Forbes for their help with computer programming.

TARGET STRENGTH MEASUREMENTS OF HERRING AND CAPELIN *IN SITU* AT ICELAND

by

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ABSTRACT

This paper presents measurements of the mean target strength of several separate length groups of herring and capelin *in situ*. The statistical model by Craig and Forbes is used in the calculations. A functional relationship between target strength and fish length is established. Possible errors are discussed.

A study of avoidance reaction and tilt angles was undertaken using a graphic recorder.

Comparison with target strengths reported by other workers is made and the differences discussed.

The importance of the knowledge of tilt angles and the awareness of possible reaction of the fish due to the ships passage is stressed when doing target strength measurements.

RESUME

Ce rapport présente des mesures sur l'index de réflexion moyen des groupes de hareng et de capelan de longueurs différentes. Le modèle statistique de Craig et Forbes est utilisé pour le calcul. Une relation fonctionnelle entre le pouvoir réflecteur et la longueur du poisson est établie. Les erreurs possibles sont discutées.

Une étude est faite sur l'effroi du poisson et sur des angles d'inclinaison en utilisant un enregistreur graphique.

Les résultats obtenus sont comparés avec les résultats des autres chercheurs et la différence discutée.

L'importance de la connaissance des angles d'inclinaison et de comportement du poisson par rapport au bateau est soulignée.

1. INTRODUCTION

In recent years acoustic stock size estimates of fish populations have become very important for rational management of certain fish stocks. In order to convert echo intensities to fish abundance a good knowledge of the *mean* acoustic target strength of the species in question is needed.

Different methods have been tried for converting the backscattered acoustic energy from fish into numbers or tonnage. One can distinguish between two categories:

a) Measurements of fish in controlled experiments, i.e. target strength measurements on dead or stunned single fish, (Midttun and Hoff, 1962; Nakken and Olsen, 1977; Foote and Nakken, 1978) and integration of caged fish (Johannesson and Losse, 1977; Røttingen, 1976).

b) Measurements of fish in their natural environment, i.e. counting of single fish traces from echograms combined with echo integration - "The Bergen Method" - (Midttun and Nakken 1971) and target strength measurements (Craig and Forbes, 1969; Ehrenberg 1974).

It has been shown that the magnitude of the backscattered energy from the fish is strongly dependent on its behaviour pattern (Olsen 1979, 1980, 1981; Foote 1979, 1980). Neglecting this can result in large errors when estimating absolute fish densities. One way of incorporating the behaviour pattern is by measuring the mean target strength of a free swimming individual fish and assume that the fish tilt angle distribution are the same for scattered and schooled fish.

Since 1973 acoustic surveying of the size of the Icelandic summer spawning herring stock has been carried out (Jakobsson, 1982) and of the Icelandic capelin stock since 1978 (Vilhjálmsson *et al.*, 1982).

In order to obtain more information on the acoustic properties of these species a series of target strength measurements of fish *in situ* have been carried out.

In this paper the results of these measurements are presented. The measurements were carried out in November and December in 1980 and 1981 and in January 1982.

2. MATERIALS AND METHODS

All measurements were carried out on board the Icelandic research vessel Arni Frioriksson. All were done by night when the fish was frequently found in sufficiently thin scattering layers (Fig. 1).

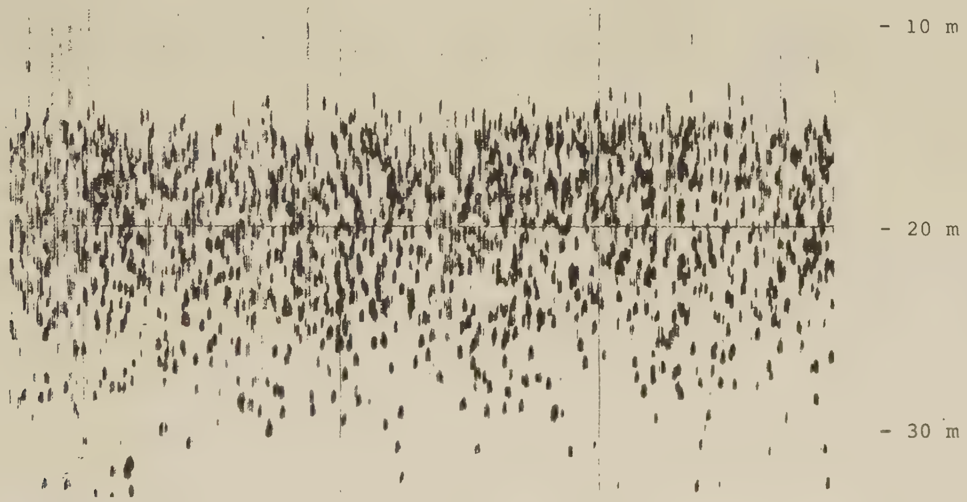

Fig. 1. Typical registration of 1 group herring in Eyjafjord.

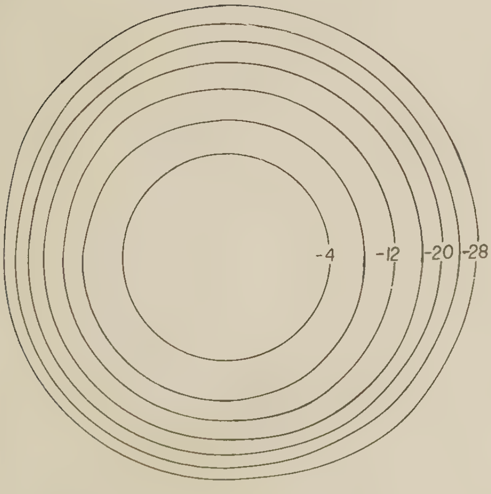

Fig. 2. Two way cross-section of an acoustic beam pattern for a SIMRAD 69 LA transducer. Sound intensity levels indicated in dB.

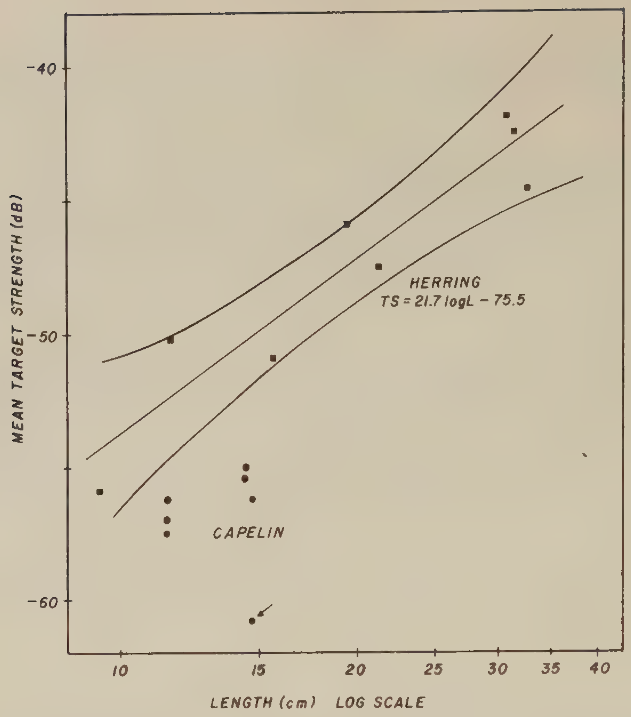

Fig. 3. Mean target strength for herring (squares) regressed on fish length. The regression is shown with a 95% confidence interval. Capelin mean target strength estimates shown as circles. (See text for fuller explanation).

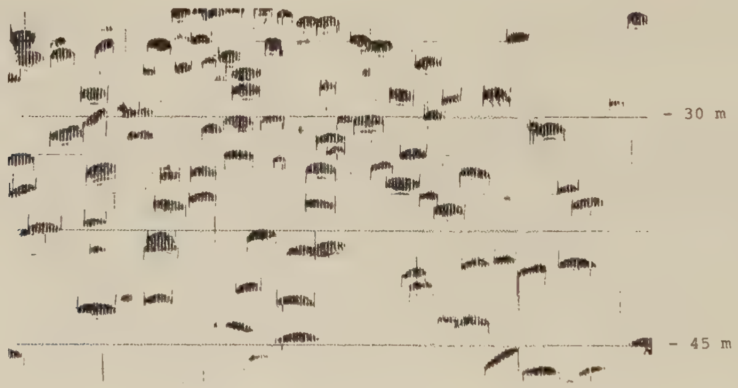

Fig. 4. Echogram from the graphic recorder showing single fish traces of 1 group herring.

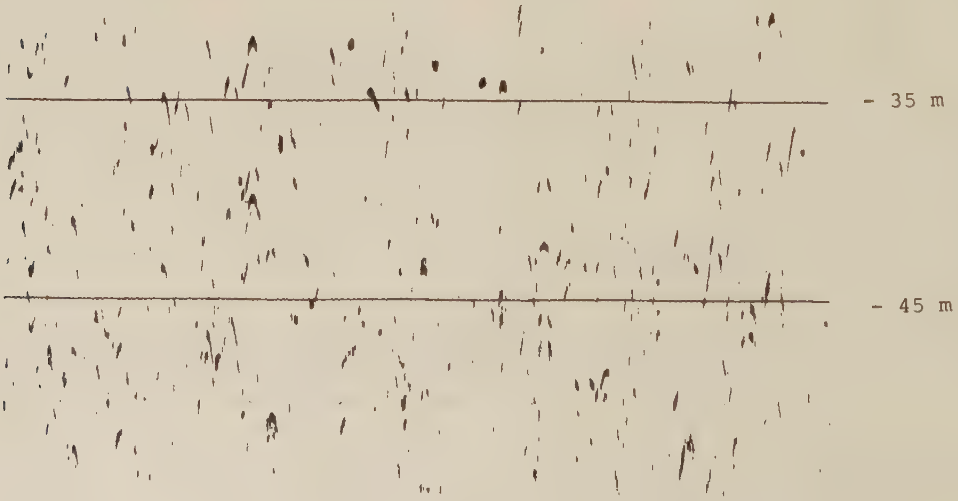

Fig. 5. Echogram of adult capelin from the first target strength measurement in January 1982.

The echo sounder used was a 38 kilohertz SIMRAD scientific sounder, with a magnetostrictive transducer, 30x30 cm and a 3 dB one way beamwidth of 7 degrees. The pulse length used was 0.6 m sec. The calibrated output from the receiver was coupled to a two channel storage oscilloscope (Hewlett-Packard 141 B). A precision graphic recorder (EG and G type 4600) with a maximum ping rate of 480 pings per minute was also used in connection with the echo sounder. The instruments were frequently calibrated during the measurements. This was done with a steel sphere with a diameter of 125 mm, and target strength -28.7 dB. The sphere was lowered down to 20 m beneath the hull-mounted transducer with three monofilament nylon lines, aligned with the acoustic axis, and the amplitude of the backscattered pulse measured. This sphere is a secondary reference target, the primary being a copper sphere with a diameter of 60 mm and target strength -33.7 dB (Foote et al., 1981). A close monitoring of the receiver's TVG-function was also maintained throughout the measurements.

The observation depths were between 10 and 50 m. Within this depth range an interval of 10 m was selected for each TS-measurement. Samples were taken using a midwater trawl, either simultaneously or immediately afterwards. About 400-500 values were obtained for each measurement and used as the basis for calculations of the mean target strength. These values were read as peak voltages from the oscilloscope and at the same time scrutinized for a definite sign of single fish echoes. They were then converted to target strength in decibels (TS) using the formula (Bodholt, 1971):

$$TS = V_{peak} - 3 - SL - VR + 40\log R + 2\alpha R + K \text{ dB}$$

TS: target strength in dB re 1 m^2 ref. 1 metre.
SL: axial source level in dB re 1µPa ref. 1 metre.
VR: axial receiver voltage response in dB re 1 volt pr. µPa.
R: maximum depth range of the receivers time varied gain.
α: logarithmic absorbtion coefficient of sound in sea water in dB pr. 1 metre.
K: time varied gain correction factor.

The TS values were grouped in 4 decibel cells, and the mean target strength calculated by using the statistical model described by Craig and Forbes (1969). The cross-sections of the acoustic beam pattern is shown in Fig. 2.

The graphic recorder was used to study in detail the behaviour of the fish during the target strength measurements. The single fish traces on this recorder were further used to calculate the mean effective beam width according to the formula:

$$\Theta = 2\text{arctg}\,\frac{\text{vessel speed (m/sec)} \cdot \text{trace length (mm)}}{2 \cdot \text{fish depth (meters)} \cdot \text{paper speed (mm/sec)}}$$

3. RESULTS

The calculated mean target strength values are shown in Tables 1 and 2 for herring and capelin respectively.

The expected relationship between target strength and fish length (1) is in the form of (Foote, 1979):

$$\overline{TS} = m \log 1 + b$$

where 1 is the fish length. Applying the least mean square linear regression on the herring values gives the following relationship between the mean target strength and the mean length in centimeters:

$$\overline{TS} = 21.7 \log 1 - 75.5 \text{ dB} \qquad (1)$$

The regression analysis for the target strength estimate is given in Table 3.

For capelin the mean TS for the two length groups are:

$$\overline{TS} = -56.9\text{dB for } 1 = 11.5 \text{ cm}$$

and $\overline{TS} = -56.6 dB$ for $l = 14.5$ cm

The TS values and the functional relationship is shown in Figure 3. The following relationship between the herring weight, in decibels relative to one kilogram, and length in centimeters at the time of the TS-measurements was found to be:

$W = 32.6 \log l - 54.6$

with a correlation coefficient $r = 1.00$

This gives:

$$\overline{TS}_{kg} = -(10.9 \log l + 20.9) \text{ dB} \qquad (2)$$

which is the expected backscattering strength in decibels from one kilogram of herring of length l. TS per kg for capelin is not thought realistic as its mean weights may vary considerably from year to year.

4. DISCUSSION

In all the calculations only TS-values inside the transducer's main lobe were included. This handling of the data was supported by analysis of single fish traces from the graphic recorder (Fig. 4). From these traces a mean beam width of 10 degrees was calculated, and a maximum detection beamwidth of approx. 14 deg., which corresponds to the lower limits of the TS distributions. In comparing the graphic recorder echograms from the different measurements it was obvious that no difference in fish behaviour in general could be detected. Further analysis shows no clear indication of avoidance reaction or different behaviour pattern in different depth intervals (Halldorsson,1982). This means that one can expect a rather narrow distribution of the fish tilt angle (Beltestad,1974).

Ehrenberg and Lytle (1977) consider that a normal distribution for the target strength in decibels using the Craig and Forbes method may be reasonable for some populations. For the present data this approach was considered to be the most convenient, although the assumption of normal distribution of the TS is not used.

When grouping the data 2, 3 and 4 dB cells were tried. All cases resulted in much the same mean target strength values. From the accumulated TS distribution it was clear that the number of values in the lowest TS-group were in some instances too low. This can be explained as due to bias introduced when reading the smallest peak values from the crt. To compensate for this bias and to avoid negative density values in calculating the mean target strength, some adjustments of the accumulated target strengths distributions were necessary. The directivity diagram available was not measured for the particular transducer used, but for the series (SIMRAD, 69LA). In view of the above some constant bias in the absolute mean target strength can not be excluded.

Nakken and Olsen (1977) report expected target strength for herring at sea to be:

$$TS = 13.6 \log l - 62.8 \text{ dB} \qquad (3)$$

The difference, ΔTS between this estimate and equation (1) is:

$$\Delta TS = 8.1 \log l - 12.7 \text{ dB}$$

Dalen, Raknes and Røttingen (1976) estimated the mean maximum dorsal target strength for 4 species from the order Clupeiformes to be:

$$TS = 19.1 \log l - 64 \text{ dB} \qquad (4)$$

if one assume 6 dB reduction, as suggested by Nakken and Olsen (1977), the difference, ΔTS, between that estimate and equation (1) will be:

$$\Delta TS = 2.6 \log l - 5.5 \text{ dB}$$

Edwards and Armstrong (1982) estimated the mean target strength per 1 kg for herring to be:

$$TS_{kg} = -17.09 \log l - 10.6 \text{ dB} \qquad (5)$$

This equation compared with the target strength per kg (eq. 2) gives the difference:

$$\Delta TS_{kg} = 6.2 \log l - 10.3 \text{ dB}$$

From these comparisons one can see that the difference in the target strength estimates is largest for the smallest herring, 2.7 to 4.6 dB for 10 cm herring. The difference is considerably reduced for the larger herring and for 35 cm herring the difference is from 0.2 to 1.5 dB. Using one of the estimates given in equations 3 to 5 would result in serious underestimation of the smallest herring compared with abundance estimates obtained by eq. 1 and 2. The difference in abundance estimates is reduced for larger herring. In the acoustic estimates of the Icelandic capelin the conversion constant used by the Norwegian scientists has been adopted. From this conversion constant and the instrument constant measured for the Icelandic research vessel "Bjarni Sæmundsson" a target strength was calculated for 11.5 and 14.5 cm capelin. This is -54.3 and -52.5 dB respectively. The difference is 2.6 and 3.0 dB and would result in a nearly twofold increase in stock size estimates. These differences, excluding the possible bias in our calculations, could be explained by varying tilt angle distribution and it is believed that the different experiments are hardly comparable without some knowledge of tilt angles. Differences in instrument calibration methods could also explain discrepancies between values obtained by various workers.

Weather conditions and sea state are important when carrying out in situ measurements (Dalen and Løvik, 1981). All our observations except those on 19-21 January 1982 were made under ideal weather conditions and in sheltered fjords. The measurements from 19 and 20 January this year were all on adult capelin when wind force of up to 20 knots prevailed. Although the roll or pitch of the ship was not pronounced, these values could be somewhat lower than in a better state of sea.

An interesting observation was made during the first TS-measurements of capelin in January 1982. This was a drastically different distribution of the accumulated TS-values than expected, much more abundant in the lower categories resulting in a lower mean target strength. This value is indicated by an arrow in Fig. 3. When studying the echogram it was evident that some downward and upward migration had occurred during the measurement (Fig. 5). It was also discovered that the working lights had not been switched off. During all other measurements both of herring and capelin only the navigation lights were showing. As mentioned earlier all the TS-measurements were done at night and the only avoidance reaction that could be detected seemed to be due to the disturbing effect of lights on board the ship, but almost certainly not because of engine or propeller noise.

Table 1. Results of herring target strength measurements. DI: depth interval for the measurement. $\bar{l}$: mean fish length. SD ($\bar{l}$): standard deviation of $\bar{l}$. $\overline{TS}$: mean target strength.

Locality		Date	DI (m)	$\bar{l}$ (cm)	SD($\bar{l}$) (cm)	$\overline{TS}$ (dB)
1	Berufjord	17.11.80	7-17	30.6	1.9	-41.9
2	Eyjafjord	19.11.80	10-20	11.6	1.6	-50.2
3	Seyoisfjord	6.12.80	40-50	9.4	0.9	-55.9
4	Mjõifjord	8.12.80	15-25	21.3	1.7	-47.5
5	Reydarfjord	9.12.80	5-25	31.3	2.4	-42.5
6	Stöovarfjord	11.12.80	25-35	32.8	2.3	-44.6
7	Eyjafjord	23.11.81	24-34	15.6	1.5	-45.9
8	Berufjord	30.11.81	30-40	19.3	1.5	-45.9

Table 2. Results of capelin target strengths measurements.
Notations as in Table 1.

Locality	Date	DI (m)	$\bar{l}$ (cm)	SD($\bar{l}$) (cm)	$\overline{\overline{TS}}$ (dB)
1 Berufjord	16.11.80	15-25	11.4	1.12	-56.2
2 Berufjord	28. 2.81	20-30	11.5	1.12	-57.5
3 64°44'N, 11°14'W	19. 1.82	35-45	14.7	1.13	-60.8
4 - - - - -	19. 1.82	25-35	14.7	1.13	-56.4
5 64°40'N, 11°49'W	20. 1.82	35-45	14.3	1.41	-55.0
6 - - - - -	- - -	25-35	14.3	1.41	-55.0
7 65°30'N, 11°12'W	21. 1.82	30-40	11.5	1.14	-57.0

Table 3. Regression analysis of mean target strength on fish length. m and b are estimated regression coefficients and S(m) standard error of estimate and r is the correlation coefficient.

Species	m	S(m)	b	SE	r
Herring	21.7	3.2	-75.5	1.8	0.94

5. CONCLUSIONS

In spite of some technical shortcomings in data sampling, and that no statistical tests were used when processing the data, we believe that the target strength values presented are in many ways characteristic for the mean backscattered energy from a thinly scattered fish distribution of the same species, having a relatively narrow length and tilt distributions.

The difference in target strength of individual herring and capelin of the same length is quite marked, and should not be biased although the absolute values can be.

It must be stressed how a slight reaction of the fish due to the passage of the vessel can greatly affect the mean target strength. Study of tilt angles is therefore of major importance when doing TS-measurements of free swimming or confined fish.

ACKNOWLEDGEMENTS

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A REVIEW OF IN SITU TARGET STRENGTH ESTIMATION TECHNIQUES

by

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ABSTRACT

The acoustic target strength of individual fish is an important parameter in most applications of acoustics to fisheries research. The results of the two commonly used quantification techniques, echo counting and echo integration, depend on the acoustic size of individual fish in the population. Fish target strength studies fall into two categories, controlled experiments and in situ measurements. In controlled experiments the fish are artificially confined. For in situ measurements the target strength is extracted from free-swimming fish. This paper reviews the various techniques that have been proposed and used for in situ target strength measurement. Each is evaluated and some recent advances in hardware and software for the various techniques are described.

RESUME

L'index de réflexion acoustique d'un poisson est un paramètre important pour la plupart des applications de l'acoustique aux recherches sur les pêcheries. Les résultats des deux méthodes de quantification souvent utilisées, comptage d'échos et intégration d'échos, sont influencés par la taille acoustique des poissons individuels dans la population. Il y a deux catégories d'études de l'index de réflexion des individus: les expériences contrôlées où les poissons sont confinés artificiellement et les mesures sur le terrain où l'on donne l'index de réflexion des poissons qui nagent sans contrainte. Cet exposé fait un rappel des diverses méthodes déjà décrites et utilisées pour les mesures de l'index de réflexion in situ. Nous évaluons chacune d'elles et nous donnons une description des progrès récents en matière d'équipement et de logiciel pour ces méthodes.

1. INTRODUCTION

The most common acoustic assessment technique used today is echo integration. It has been shown both experimentally and theoretically that the average integrated acoustic intensity scattered from a collection of fish is proportional to the average density of the fish. The constant of proportionality depends on the parameters of the acoustic system and the average back scattering cross section for individual fish in the population. Because the back scattering cross section parameter is so important, much work has been done to determine its average value as a function of fish type and size and of acoustic frequency.

Fish target strength studies fall into two categories, controlled experiments and in situ measurements. In the controlled experiments the fish are confined. In some cases, individual fish are suspended on a rigid structure and detailed measurements as a function of fish orientation and acoustic frequency are made. Another approach is to take measurements on individual or multiple fish that are confined in a pen. The results of such controlled experiments are often expressed in a regression formula that

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relates individual scattered target strength to fish length and acoustic frequency. Although such measurements have provided much useful information on the acoustic properties of various marine organisms, they do not always provide the kind of information needed for acoustic biomass assessment.

In particular, the use of results from controlled experiments requires a knowledge of the species composition and size distribution of the scatterers being assessed. Also, there is some uncertainty about the amount of correlation between the acoustic properties of three swimming fish and those artificially confined. In the 1979 meeting on Hydroacoustical Methods for the Estimation of Marine Fish Populations, a number of authors pointed to problems with using target strength measurements obtained in controlled experiments for application to free swimming fish populations (Harden Jones and Scholes 1981; Hawkins 1981; Foote 1981; Foote 1981-a). The advisory Committee on Marine Resources Research (ACMRR) for the Food and Agriculture Organization of the United Nations (FAO, 1978) has voiced a similar concern.

The alternative to the controlled measurements is to extract the target strength estimates from the acoustic returns in situ. In this paper, I review the various in situ target strength estimation techniques that have been used and proposed to date. The advantages and disadvantages of each are presented along with a discussion of the problem of isolating returns from single target. Hardware and software implementation of the techniques is also discussed.

2. IN SITU TARGET STRENGTH ESTIMATION

The intensity of an acoustic echo reflected from an individual fish is expressed by

$$I = k \frac{10^{-2\alpha R}}{R^4} b^2(\theta,\phi)\sigma_{bs} \qquad (1)$$

where k is a scale factor that can be determined during system calibration, $10^{-2\alpha R}/R^4$ is the range dependent loss due to absorption and spreading, and $b^2(\theta,\phi)$ is the acoustic system's two-way beam pattern function. The fish, with backscattering cross section σ_{bs}, is located at angular coordinates (θ,ϕ). The target strength TS and backscattering cross section σ_{bs} are related by $TS = 10 \log_{10} (\sigma_{bs})$. To obtain the backscattering cross section or target strength statistics from the received echoes of single targets, the effects of the scale factor k, the range dependent loss $10^{-2\alpha R}/R^4$, and the beam pattern function $b^2(\theta,\phi)$ must be removed from the received single target intensities. The scale factor and the range dependent loss can be removed in a conseptually straightforward manner. However, the actual implementation of this step requires accurate calibration data for the receiver's time-varied gain and the overall system's source level and gain. The beam pattern factor depends on the target's random angular location in the beam and is more difficult to deal with. A number of procedures for removing the beam pattern factor have been proposed. These techniques can be grouped into two categories: those that indirectly extract the effect of the beam pattern from a collection of echoes, and methods that directly remove the beam pattern from each individual echo.

3. INDIRECT TARGET STRENGTH ESTIMATION

The appeal of the indirect target strength estimation techniques is that they can be implemented with the same single-transducer echo-sounding systems that are used for population quantification. A number of different approaches have been proposed for indirectly extracting the backscattering cross section from a collection of individual echoes. All of the techniques published to date assume that the scatterers are uniformly distributed in the acoustically illuminated volume. Using this assumption and the transducer directivity function, it is possible to determine the required statistical properties of the beam pattern term in Eq. 1. There have been two different approaches for dealing with the backscattering cross section variable σ_{bs}. In one approach, the statistics of σ_{bs} are assumed to be unknown, and an estimate of the probability distribution or density for σ_{bs} or TS is formed. Craig and Forbes (1969) were the first to use this approach. In their technique, the echo intensity is expressed in decibels, with E = T+D, where

$$E = 10 \log_{10} I, \quad T = 10 \log_{10} k\sigma_{bs}, \quad D = 10 \log_{10} b^2(\theta,\phi)$$

They used the geometry of the acoustic beam to determine the relationship between the distributions of E, T, and D. If one approaches the problem mathematically, the following relationship for the probability densities of E, T, and D is found.

$$P_E(e) = \int_{\infty}^{\infty} P_T(x) P_D(x-e)\,dx \tag{2}$$

The integral equation (2) reduces to a set of linear equations that is equivalent to Craig and Forbes' formulation if it is assumed that $P_E(e)$, $P_T(f)$ and $P_D(d)$ are piecewise constant functions. Using this piecewise linear approximation, a histogram of the echo intensities in decibles forms an estimate of $P_E(e)$; $P_D(d)$ can be calculated from the beam pattern directivity functions and the assumption of a uniform scattering distribution. The resulting system of linear equations can be easily solved.

Alternate procedures were proposed by Ehrenberg (1972) and later by Robinson (1978). In their methods, an integral equation relating the backscattering cross section and echo intensity (rather than log intensity) was developed. This equation was solved using polynomial approximations to the various density functions.

All of these techniques for indirectly estimating the target strength or backscattering cross section density function are susceptible to numerical and statistical error. They do not work well in many cases of interest.

The other approach for indirectly determining the backscattering cross section factor from Eq. 1 is to assume that σ_{bs} has a particular functional form. The problem then becomes one of estimating the parameters of that assumed distribution for σ_{bs}. When the size of the single target is large compared with the acoustic wavelength, it can be argued that the single echo pressure amplitudes are Gaussian distributed and that the echo envelopes are Rayleigh distributed. With this assumption, the problem of determining the distribution of σ_{bs} reduces to one of estimating a single unknown parameter in the Rayleigh distribution of single echo envelope amplitudes. Peterson et al. (1976) were the first to use this approach. Their technique was to adjust the unknown parameter until the theoretical density function for the echo amplitudes and the measured histogram most closely agreed. Ehrenberg et al. (1981) have developed some other versions of this technique that are easier to implement and more accurate. A description of the modified techniques, along with a further discussion of the underlying assumptions, is contained in a separate paper for this symposium (Ehrenberg, 1982a).

4. DIRECT TARGET STRENGTH ESTIMATION

The alternative to the indirect method is to remove the beam pattern effect for each individual echo. In so doing, many of the problems encountered in the indirect techniques are avoided. Unfortunately, the direct target strength estimation cannot be done without some modification to the basic acoustic systems used in echo counting or echo integration.

The simplest configuration currently used for direct target strength estimation employs a duel beam transducer with two receiving channels in the echo sounder (Ehrenberg, 1974). Some typical beam patterns for a duel beam system operating at 105 kHz are shown in Fig. 1. The acoustic signal is transmitted with the narrow beam transducer and is received on both the narrow and wide beam simultaneously. The beam pattern factor for the wide beam is approximately constant over the main lobe of the narrow beam (the angular region where single echoes are detected). The system is calibrated such that the outputs for the narrow and wide beam channels are equal for an on-axis target. Under these conditions, and assuming ideal time-varied gain charac-

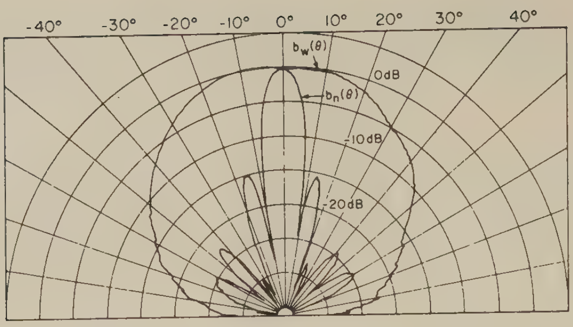


Fig. 1. Beam patterns for the 105 kHz dual beam transducer.

teristics, the narrow and wide beam echo intensities for a target at angular coordinates θ and ϕ are

$$I_N = kb^2(\theta,\phi)\sigma_{bs}$$
$$I_W = kb(\theta,\phi)\sigma_{bs} \qquad (3)$$

where k is a constant, b(θ,ϕ) is the beam pattern factor for the narrow beam transducer, and σ_{bs} is the backscattering cross section for the fish. The beam pattern factor can therefore be obtained by taking the ratio of two intensities:

$$\frac{I_N}{I_W} = \frac{kb^2(\theta,\phi)\sigma_{bs}}{kb(\theta,\phi)\sigma_{bs}} = b(\theta,\phi) \qquad (4)$$

The backscattering cross section is found by removing the beam pattern factor and the constant k from I_N or I_W:

$$\sigma_{bs} = \frac{I_W}{kb(\theta,\phi)} = \frac{I_W}{k(I_N/I_W)} = \frac{I_W^2}{kI_N} \qquad (5)$$

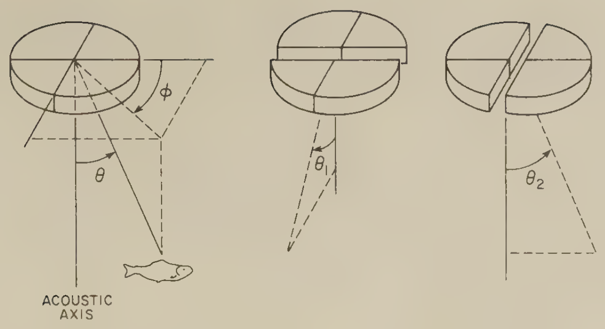
Dual beam target strength measurement systems operating at 38, 105 and 120 kHz have been built.

Results for the 105 kHz system for standard targets, adult sockeye salmon, and adult Pacific herring have been reported by Drew (1980). Results for the 38 kHz system for standard targets, walleye pollock, and Pacific whiting have been reported by Traynor and Ehrenberg (1979), and by Ehrenberg et al. (1981).

Another direct method uses a receiving transducer that has been divided into four quadrants (Carlson and Jackson, 1980; Ehrenberg, 1981). A pictorial representation of the four-quadrant transducer in the three configurations in which it is used for the split beam system is shown in Fig. 2. All four quadrants are driven simultaneously for transmission. The backscattered signals are received by each quadrant individually. The individual outputs are combined to form a full beam and two split beam sets. Single targets are isolated using the full beam output.

The angular locations (θ_1,θ_2) of each single target in the perpendicular planes are determined by measuring the phase difference $\Delta\theta_e$ in the signals out of the two halves of the transducer. The relationship between the angular location θ_L and the electrical phase difference $\Delta\theta_e$ is

$$\theta_L = \sin^{-1}\left(\frac{c\Delta\theta_e}{\omega_o d}\right) \qquad (6)$$



FULL BEAM CONFIGURATION
(TARGET LOCATION SPECIFIED
BY SPHERICAL COORDINATES)

SPLIT BEAM CONFIGURATIONS
(TARGET LOCATION SPECIFIED
BY ANGLES IN PERPENDICULAR PLANES)

Fig. 2. Representation of transducer configuration for full beam and split beam systems.

where

c = velocity of propagation

ω_o = angular frequency, $2\pi f_o$, where f_o is the acoustic frequency

d = distance between the acoustic centers of the two transducer halves

In most cases of interest, θ_L will be small and

$$\theta_L \cong \frac{c\Delta\theta_e}{\omega_o d} \tag{7}$$

Angular locations of targets are usually measured using spherical coordinates θ and ϕ, which can be expressed in terms of θ_1 and θ_2:

$$\theta = \sin^{-1} \sqrt{\sin^2\theta_1 + \sin^2\theta_2} \tag{8}$$

$$\phi = \tan^{-1}(\sin\theta_1/\sin\theta_2) \tag{9}$$

For angles near the acoustic axis, the small angle approximation for the tangent and sine can be used to yield

$$\theta \cong \left(\theta_1^2 + \theta_2^2\right)^{1/2} \tag{10}$$

$$\phi \cong \tan^{-1}(\theta_1/\theta_2) \tag{11}$$

The transducer beam pattern factor $b(\theta,\phi)$ for a single target at angular location θ,ϕ can be estimated using the measured values of θ_1 and θ_2, Eqs. 10 and 11, and the measured directivity pattern for the transducer.

The split beam system is more difficult to implement than the dual beam technique. The hardest part is implementing the hardware and/or software for measuring the phase difference between the signals received on the two half beams. The approach that works best from both a theoretical and practical standpoint involves sampling the signals out of each half beam at an interval corresponding to a 90° phase shift at the carrier frequency. Using these separated samples (quadrature samples), it is possible to determine the phase of each half beam signal and consequently the phase difference between half beams. This technique has been used by Carlson and Jackson (1980) to analyze some recorded split beam data. This analysis technique requires multiple processing of the data and will not operate in real time. Some work on real time implementation of the split beam technique has been done and is described later here.

Although the split beam method is difficult to implement, its distinct advantage is that it performs better than the dual beam in the presence of noise. The relative effect of noise on the two techniques has been determined both by analysis and through Monte Carlo simulation (Ehrenberg, 1979).

5. HARDWARE AND SOFTWARE CONSIDERATIONS

In the past, the selection of the acoustic system for a particular application was often based on cost and hardware complexity rather than on theoretical performance. Consequently, most in situ target strength measurements have been obtained using an indirect technique, which only requires a standard echo sounder and a storage, or memory, oscilloscope. The simplest direct technique (the dual beam system) requires a nonstandard transducer (or two transducers) and two sets of receiving electronics. The dual beam sounder output can be processed manually with a dual channel memory scope. However it is much simpler to use an automatic processing system. A common procedure has been to record the dual beam sounder output on an analog tape recorder and then process the recorded tape later in the laboratory using a small computer system (Drew, 1980; Traynor and Ehrenberg, 1979). Recent advances in digital electronics and microprocessors are lowering the cost of real time processing systems. It is now possible to design small, relatively inexpensive systems that can do what only a few years ago required a rather sophisticated and expensive computer system. One such example is a dual beam target strength data collection system recently built by Ehrenberg and Yee (Yee, 1981). The system is portable and can be used for either collecting data in the field or analyzing prerecorded data. A commercial version of this system has been built by BioSonics.

This system processes the two outputs of a dual beam echo sounder to determine when a single echo is present (using the pulse width criterion at two pulse amplitudes). When a single echo is detected, the system measures the narrow and wide pulse amplitudes, pulse widths, and the depth of the target. This information is then written onto a digital cassette. The cassette can be analyzed later using almost any computer -- even a small microcomputer. Compared with other techniques, the computer time required for data analysis is less by orders of magnitude. Processing dual beam, analog data recorded on tape requires an hour of processing for each hour of data. Processing the digital cassettes will usually take less than a minute for each hour of data (the actual time depends on the number of single target signals recorded and the computer's speed). The system can also be used to process single channel data. In this case, the processor detects single echoes, and records their amplitude, pulse width, and the depth. The recorded single channel data can be processed using any of the indirect target strength measurement techniques discussed earlier.

Microprocessor technology is also being considered for implementing the split beam target strength measurement system. One approach uses a microprocessor to detect single echoes, measure the electrical phase difference between half beam signals, and calculate the target's angular location and depth. This information could either be recorded on digital cassette or directly transferred to another microprocessor or microcomputer for further processing.

6. CONCLUSIONS

Several techniques have been proposed and implemented for making in situ measurements of the target strength of individual fish. In general, the direct techniques, in which the beam pattern effect is removed from each received single echo, are more accurate and can be applied to a wider range of populations than the indirect techniques. The indirect techniques are easier to implement and in some cases provide perfectly adequate estimates of the individual fish average backscattering cross section. However, the recent advances in digital processing hardware and software have greatly reduced the cost and difficulty of implementing many of the in situ techniques discussed here. Due to these advances, in situ target strength measurement will have an ever increasing role in acoustic stock assessment techniques.

NEW METHODS FOR INDIRECTLY MEASURING THE MEAN ACOUSTIC BACKSCATTERING CROSS SECTION OF FISH

by

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ABSTRACT

Some new procedures for indirectly extracting the average backscattering cross section from received echo amplitudes are described. The techniques are based on the assumption that the on-axis echo envelope amplitude of single fish is Rayleigh distributed. The Rayleigh assumption is best satisfied when the ratio of fish length to acoustic wavelength is large. Results of a Monte Carlo simulation of the techniques are presented along with some results for actual data.

RESUME

Nous décrivons quelques méthodes nouvelles de détermination indirecte de la section de diffusion moyenne en retour à partir des amplitudes des échos mesurés. Nos calculs reposent sur l'hypothèse que l'amplitude de l'enveloppe de l'écho des poissons individuels dans la direction principale est conforme a la distribution de Rayleigh. L'hypothèse est d'autant mieux satisfaite que le rapport entre la longueur des poissons et la longueur d'onde est grand. Nous présentons ici les résultats déterminés à partir d'une simulation de Monte Carlo, ainsi que d'autres obtenus pour des données réelles.

1. INTRODUCTION

The average acoustic backscattering cross section for individual fish in a population is one of the most important parameters for obtaining population size estimates from acoustic backscattered signals. Consequently, much effort has been expended on developing techniques for making _in situ_ measurements of the backscattering cross section of individual fish. The most commonly used or proposed methods for making such measurements are described in another paper prepared for this conference (Ehrenberg, 1983). New methods for determining the average _in situ_ scattering cross section are presented here.

The methods are developed by assuming that the intensity of an acoustic echo reflected from an individual fish is

$$I = k\frac{10^{-2\alpha_o R}}{R^4} b^2(\theta,\phi)\sigma_{bs} , \qquad (1)$$

where k is a known scale factor, and $b^2(\theta,\phi)$ is the acoustic system's combined transmitting and receiving beam pattern functions. The fish, with backscattering cross section σ_{bs}, is located at angular coordinates (θ,ϕ), and $10^{-2\alpha_o R}/R^4$ is the loss due to absorption and spreading. To obtain σ_{bs} from the echo intensity, the effects of the scale factor, range-dependent losses, and beam pattern must be removed. The scale factor and the range-dependent losses are deterministic factors that can be removed by a time-varied gain. The beam pattern factor, however, depends on the scatterer's random angular location relative to the acoustic axis of the system. The beam pattern

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effect can be removed directly from each individual echo or indirectly by processing a collection of individual echoes. The primary advantage of the indirect techniques is that they can be employed with the same basic echo sounding system used for echo counting or echo integration. The main disadvantage of the indirect methods is that they produce a less accurate estimate than the direct techniques.

Craig and Forbes (1969) were the first to use an indirect target strength (target strength = 10 log σ_{bs}). Their technique provides a way of estimating the target strength probability density function by removing the effect of the beam pattern from the histogram of single fish echo levels. Other methods for extracting the target strength probability density from a collection of echo levels have been proposed by Ehrenberg (1972) and Robinson (1978). All of these procedures are similar in that they make no assumption about the underlying distribution for σ_{bs}.

Peterson et al. developed a technique that assumed that the form of the probability density for σ_{bs} was known (Peterson et al., 1976). They noted that when the size of the fish is large compared with the acoustic wavelength, the total scattered acoustic pressure will be the sum of smaller pressure levels scattered from various parts of the fish. When the number of individual scattered pressure level is large, the total pressure amplitude will have a Gaussian probability density function according to the central limit theorem. The backscattering cross section is proportional to the pressure squared and is therefore X^2 distributed. The pressure envelope is proportional to $\sqrt{\sigma_{bs}}$ and is Rayleigh distributed. The validity of the Rayleigh assumption as a function of fish-length-to-wavelength ratio is considered later in this paper. The advantage of assuming a particular distribution for σ_{bs} is that it should be easier to estimate a parameter of an underlying distribution than it is to estimate the entire distribution. This paper presents some techniques for estimating the underlying parameter of the Rayleigh distribution. These methods are more accurate and easier to implement than the procedure orginially proposed by Peterson et al. (1976).

2. THE ESTIMATION TECHNIQUES

The echo envelope level for a single fish target with the effects of the range dependent loss removed by a time-varied gain is

$$E = C\sqrt{\sigma_{bs}}\, b(\theta,\phi) \qquad (2)$$

where C is a constant that can be determined during system calibration. To simplify notation, define a new random variable $A = C\sqrt{\sigma_{bs}}$. From the discussion in the previous section it follows that A is Rayleigh distributed. That is, the probability density for A is

$$p_A(a) = \begin{cases} \dfrac{a e^{-a^2/\overline{A^2}}}{\overline{A^2}/2} & a \geq 0 \\ 0 & a < 0 \end{cases} \qquad (3)$$

where $\overline{A^2} = C^2\bar{\sigma}_{bs}$. The probability density for the beam pattern factor $b(\theta,\phi)$ can be found from the transducer directivity function and an assumed distribution of fish in the ensonified volume. An expression for the beam pattern factor density for a circular piston transducer and a uniform distribution of scatterers is given in (Ehrenberg et al., 1981). The theoretical distribution for the echo envelope level E, which can be calculated using the densities for A and $b(\theta,\phi)$, is a function of the single parameter in the Rayleigh distribution, $\overline{A^2} = C^2\bar{\sigma}_{bs}$. The backscattering cross section can therefore be found by adjusting the $\overline{A^2}$ parameter in the Rayleigh density until the theoretical and measured values of the echo level variable agree in some statistical sense. Matching the theoretical and measured statistics for E is complicated by the fact that only echoes that exceed some threshold determined by the system noise and the dynamic range of the electronics will be detected. However, some general procedures for estimating σ_{bs} can be developed by using the following normalized variables for the echo level and the backscattering cross section variable:

$$\tilde{A} = \sqrt{A^2/E_{min}} \qquad (4)$$

$$\tilde{E} = E/E_{min}$$

The value of E_{min} is chosen to be sufficiently above the noise level to assure that all single target echoes with aplitudes greater than E_{min} are detected. It can be shown (Ehrenberg et al., 1981) that the probability density function for the normalized echo amplitude is

$$p_{\tilde{E}}(\tilde{e}) = k_1 \tilde{e}^{1-2C_0} \Gamma(C_0, \tilde{e}^2/\tilde{A}^2) \, , \qquad \tilde{e} \geq 1 \qquad (5)$$

where k_1 and C_0 are constants (C_0 is a constant in the beam pattern density and is approximately 0.895 for circular transducers with a 3 dB beam width of 20° or less), and $\Gamma(\alpha,\beta)$ is the incomplete gamma function. It should be noted that the density in Eq. 5 is a function of only the normalized envelope and backscattering cross section variables; it does not depend on system gains or the actual value of the Rayleigh parameter.

One of the simplest ways to determine the value of $\tilde{A}$ that provides a match between the measured normalized echo levels and the density in Eq. 5 uses the moments of $\tilde{E}$. The i^{th} moment for the density in Eq. 5 is

$$\overline{\tilde{E}^i} = \int_1^\infty \tilde{e}^i \, p_{\tilde{E}}(\tilde{e}) d\tilde{e} \qquad (6)$$

The first and second moments as a function of $\tilde{A}$ are plotted in Fig. 1. To use these curves, one first estimates the first and/or second moments from the received envelope amplitude data.

$$\hat{\tilde{E}} = \frac{1}{N} \sum_{j=1}^{N} E_j/E_{min} \, , \qquad E_j/E_{min} \geq 1 \qquad (7)$$

$$\hat{\tilde{E}^2} = \frac{1}{N} \sum_{j=1}^{N} (E_j/E_{min})^2 \, , \qquad E_j/E_{min} \geq 1 \qquad (8)$$

Next, find the corresponding value of $\tilde{A}$ using the estimated moments and the curves in Fig. 1. The backscattering cross section estimate is then given by

$$\hat{\sigma}_{bs} = \frac{\tilde{A}^2 \, E_{min}^2}{C^2} \qquad (9)$$

The value of $\tilde{A}$ can also be determined by matching the calculated probability distribution and measured empirical distributions for $\tilde{E}$. The probability distribution $P_{\tilde{E}}(\tilde{e})$ is obtained by integrating Eq. 5.

$$p_{\tilde{E}}(\tilde{e}) = k_1 \int_1^{\tilde{e}} p_{\tilde{E}}(\alpha) d\alpha \, , \qquad \tilde{e} \geq 1 \qquad (10)$$

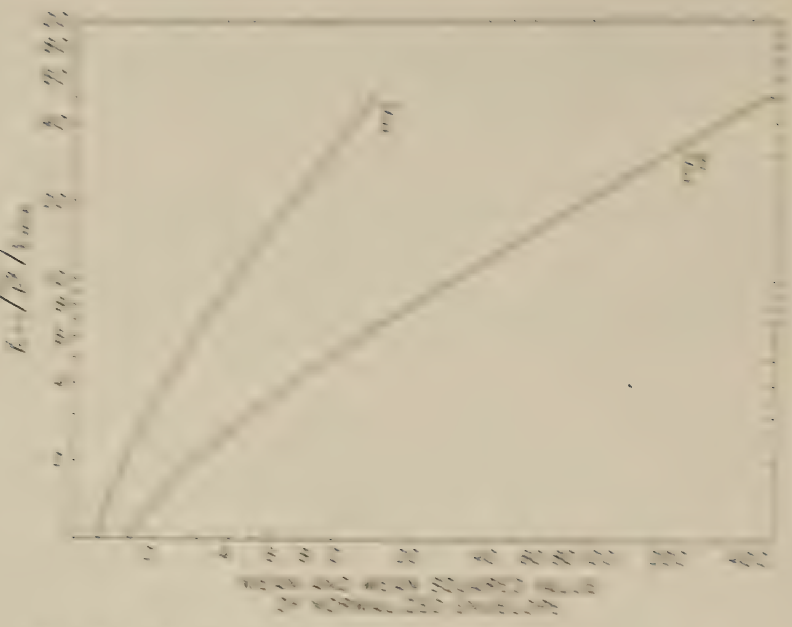

Fig. 1. Curves for determining the mean of the backscattering cross section variable from the mean and mean squared values of normalized echo envelope amplitude.

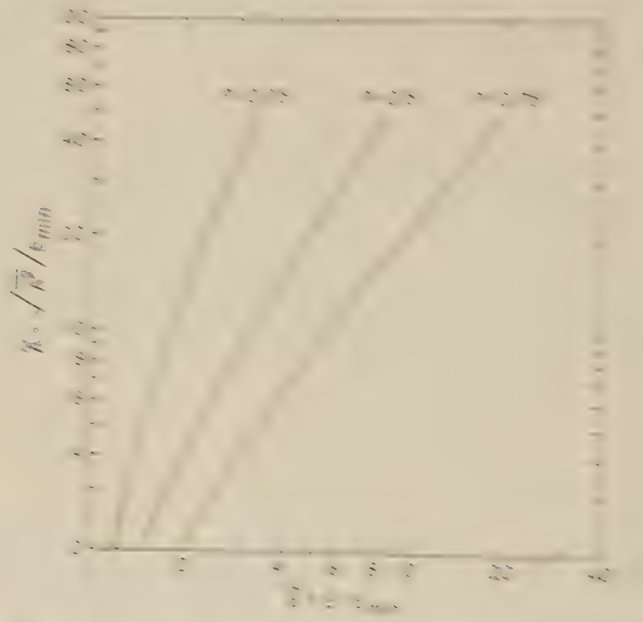

Fig. 2. Curves for determining the mean of the backscattering cross section variable from the normalized echo envelope amplitude $\bar{x}$ at various probability distribution levels P.

Curves relating $\bar{x}$ to $\bar{k}$ for various values of the empirical distribution P are shown in Fig. 2. Estimates of $\bar{\sigma}_{bs}$ are obtained by forming the empirical distributions for the normalized echo envelope amplitudes of a single target. The value of x at P = 0.25, 0.5 or 0.75 is determined from the empirical distribution. The curves in Fig. 2 are then used to find the corresponding values of k; Eq. (7) is used to find $\bar{\sigma}_{bs}$. The estimation procedure that used the empirical distribution has been discussed in more detail in previous papers (Ehrenberg *et al.*, 1981 and Ehrenberg *et al.*, 1980).

A critical assumption in the methods described here is that the amplitude of the echo envelope from on-axis single fish is Rayleigh distributed. In the summer of 1978, Carlson (Carlson, 1978 and Ehrenberg *et al.*, 1981) conducted a large number of controlled measurements of the peak amplitude of the echo envelope of several rainbow trout at dorsal aspect. The empirical distributions of these measurements were tested for their fit to a Rayleigh distribution. Carlson found that the fit to the Rayleigh distribution was best when the ratio of fish length to wavelength was large (greater than 25).

3. MONTE CARLO SIMULATION

A Monte Carlo simulation was conducted to investigate the relative performance of Craig and Forbes' target strength estimation method and the methods described here (Ehrenberg *et al.*, 1980). For the simulation, the on-axis echo envelope amplitude was Rayleigh distributed. The simulation was done for various sample sizes N and various values of the normalized backscattering cross section $\tilde{A}^2$. The technique based on the Rayleigh assumption obtained the estimate by forming the empirical distribution for the normalized echo levels and using the P = 0.5 curve in Fig. 2. Craig and Forbes' technique used a 2 dB cell width for the echo level and target strength histograms. The simulation study is described in greater detail in a paper by Ehrenberg *et al.*, (1980).

Some results of the simulation are shown in Figs. 3-4. The effect of sample size on the bias (Fig. 3) and standard deviation (Fig. 4) of the estimate is presented for the two techniques. The performance of the method using the Rayleigh assumption was superior to that of Craig and Forbes. The simulation results for the Rayleigh-based method have been compared with some theoretical results for bias and standard deviation and they agree quite well. The main limitation of the simulation study is that it does not show the performance of the new technique when the assumed Rayleigh distribution for $\sqrt{\sigma_{bs}}$ is not satisfied. Some results for actual fish populations are presented in the next section to provide insight into this question.

4. FIELD RESULTS

Results for two different applications of the indirect backscattering cross section estimation techniques are presented in this section. The two examples further illustrate the effect of the fish-length-to-wavelength ratio on the accuracy of the technique.

The first example will be for some single fish echo level data collected in Lake Washington in the summer of 1979. The fish present in the part of the lake that was surveyed were adult sockeye salmon with a mean length of 55 cm and a mean weight of 2.3 kg. Using a 105 kHz dual beam echo sounding system, the data were collected by slowly drifting over the fish. About ten echoes were processed for each target. The average fish-length-to-acoustic-wavelength ratio for the population is 38.5. An earlier study (Ehrenberg *et al.*, 1981) indicates that the Rayleigh assumption should be valid for this population. The received echoes were processed by a 40 log R time-varied gain to remove the range dependent loss from the echo level. The system gain was adjusted such that a -30 dB target (σ_{bs}=0.001) produced an on-axis echo envelope voltage of 5.0 volts. The minimum echo level threshold was set at 0.3 volt. The mean, mean squared, and empirical distribution for the normalized echo level $\tilde{E}$ were calculated from a sample of 144 echoes. The corresponding values for the normalized scattering cross section variable $\tilde{A}^2$ were determined using the curves in Figs. 1 and 2. The values of average backscattering were found from E_{min} and the system gain. The results are summarized in Table 1. The data were also processed using the dual beam technique. The dual beam technique directly obtains an estimate of the backscattering cross section for each individual echo and does not depend on any assumption for the statistical distribution of $b(\theta,\phi)$ or σ_{bs}. The average backscattering cross section estimate for the dual beam technique was 0.00105 (10 log σ_{bs} = -29.762). The fact that the five estimates summarized in Table 1 and the dual beam estimate closely agree shows

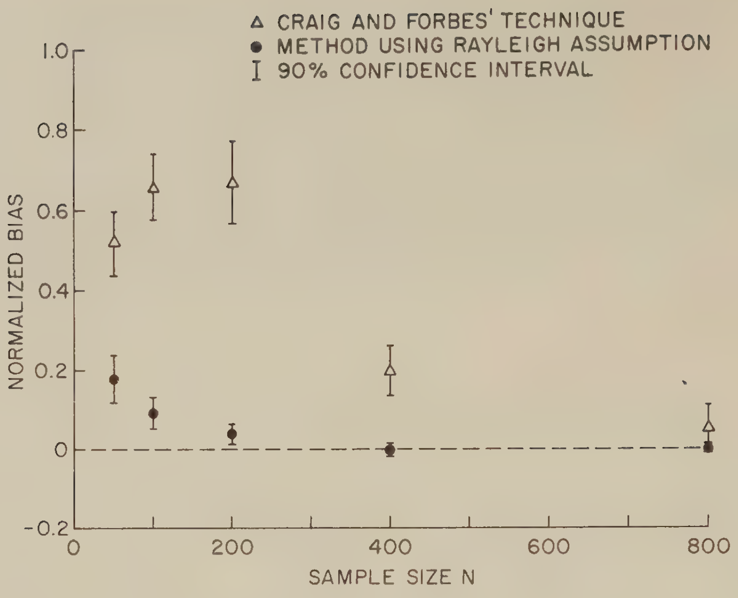

Fig. 3. Normalized bias as a function of sample size N for a fixed $\tilde{A}^2 = 64$.

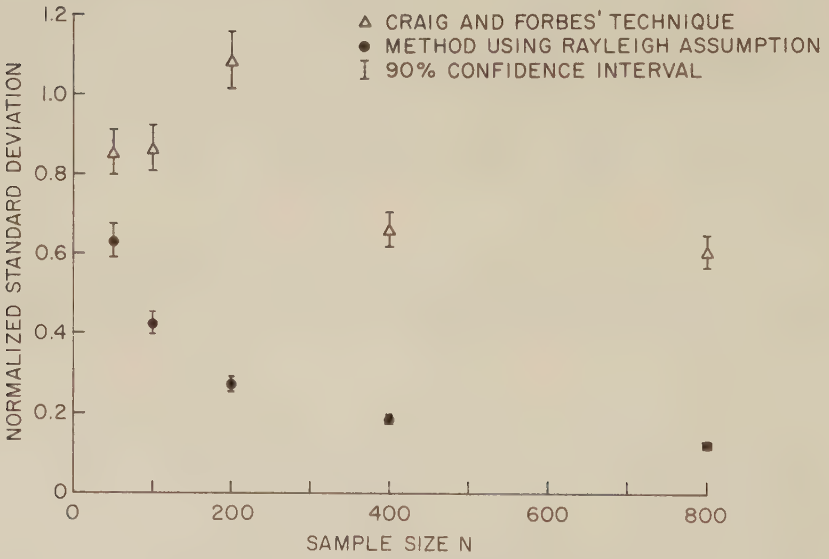

Fig. 4. Normalized standard deviation as a function of sample size N for a fixed $\tilde{A}^2 = 64$.

that the underlying assumptions used in obtaining the indirect techniques were probably satisfied for this population.

To determine the effectiveness of the indirect technique when the fish-length-to-wavelength ratio is smaller, some data collected using a dual beam 38 kHz sounding system were analyzed. These data were collected by Traynor about 40 km north of Adak Island in the Bering Sea in June 1979 (Ehrenberg *et al.*, 1981). The fish in the population surveyed were walleye pollock with a mean length of 47.7 cm and a mean weight of 0.64 kg. The fish-length-to-wavelength ratio for this population was 12. An earlier study predicts that the Rayleigh assumption is probably not valid for this size fish at a 38 kHz acoustic frequency. Four samples of 1000 single fish echoes each were

Table 1. Summary of *in situ* indirect backscattering cross section estimates for 55 cm sockeye salmon obtained using a 105 kHz acoustic system.

Measurement Statistic	Value of Statistic	$\tilde{A}$	$\hat{\sigma}_{bs}$	10 log $\hat{\sigma}_{bs}$
$\hat{\tilde{E}}$	6.46	18.5	0.00123	-29.1 dB
$\hat{\tilde{E}}^2$	74.60	18.0	0.00117	-29.3 dB
$\tilde{E}$ at $P = 0.25$	2.30	21.0	0.00158	-28.0 dB
$\tilde{E}$ at $P = 0.50$	4.80	21.2	0.00162	-27.9 dB
$\tilde{E}$ at $P = 0.75$	9.00	18.5	0.00123	-29.1 dB

processed using the empirical distribution and the curves in Fig. 2. The data were also processed with a dual beam direct technique. The data collection and processing procedures are described in greater detail by Ehrenberg *et al.*, (1981). The results are summarized in Table 2. The estimates obtained using the dual beam technique were between -30.9 and -32.1 dB for the four sets of data. The estimates obtained with the indirect techniques varied between -27.2 dB (for $P = 0.75$ and sample 1) to -33.8 dB (for $P = 0.25$ and sample 2). If the on-axis echo envelope amplitude were indeed a Rayleigh distributed random variable, there would be little difference in the estimates at the three distribution percentiles. The large differences in the estimates for different values of P indicate that the Rayleigh assumption is not valid. The square roots of the backscattering cross section estimates obtained using the dual beam data were tested to determine if they were Rayleigh distributed. The null hypothesis of a Rayleigh distribution was rejected at the 0.01 significance level using a Kolmogorov-Smirnov goodness-of-fit test.

Table 2. Summary of *in situ* dual beam and indirect target strength estimates for 48 cm walleye pollock obtained using a 38 kHz acoustic system.

Indirect Technique

Sample Number	Sample Size	10 log ($\hat{\sigma}_{bs}$) (dB) $P = 0.25$	 $P = 0.5$	 $P = 0.75$
1	330	-33.0	-29.8	-27.2
2	382	-32.6	-31.1	-28.4
3	341	-33.8	-32.0	-28.8
4	352	-33.7	-31.6	-29.3

Dual Beam Technique

Sample Number	Sample Size	10 log ($\hat{\sigma}_{bs}$) (dB)
1	432	-31.7
2	500	-31.7
3	453	-32.1
4	349	-30.9

5. DISCUSSION

The indirect methods for processing echo envelope amplitudes of single fish to obtain average backscattering cross section estimates could be incorporated in most acoustic assessment systems. The methods can use the same transducer and echo sounder employed to acquire data for echo integration abundance estimation. The sounder's output must be processed to detect single target echoes and determine their envelope amplitudes. This processing can be done manually by an operator using a memory scope or automatically with a microcomputer or minicomputer. Some of the automatic methods for detecting and processing single fish echoes are discussed in another paper prepared for this conference (Ehrenberg, 1982).

Although the techniques described here are easy to impliment, they should only be employed when the assumption of uniform fish size and Rayleigh-distributed on-axis echo envelopes hold. The Rayleigh assumption will most likely be valid when the fish-length-to-wavelength ratio is large (greater than 25). It may be possible to modify the procedures so that they apply for a smaller fish-length-to-wavelength ratio. The modification would require a more general model for the on-axis echo envelope density function. The density would have to be a function of more than one parameter and would have to include the Rayleigh density as a special case.

ACKNOWLEDGEMENTS

Dr. Ehrenberg's research on in situ target strength estimation was supported by the National Oceanic and Atmospheric Administration through the National Marine Fisheries Service under contract 81-ABC-00133, and by the Washington State Sea Grant Program (grant NA 81 AA-D-00030). The author thanks J. Burwell, T. Carlson, A. Drew, J. Traynor and N. Williamson for their assistance in collecting and analyzing some of the data presented in this paper.

IN SITU MEASUREMENTS OF THE TARGET STRENGTHS OF PELAGIC FISHES

by

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ABSTRACT

This paper discusses the problems associated with in situ measurement of fish target strengths. One such technique involving the statistical removal of the effects of transducer directivity from the received echoes on a single beam transducer is then described. Details of the application of this techniques to the measurement of blue whiting (*Micromesistius poutassou* (Risso)) and sprat (*Sprattus sprattus* L.) target strengths are described and results, together with estimates of accuracy are presented.

RESUME

Cette communication traite des problèmes associés à la mesure *in situ* de l'index de réflexion des poissons. Une technique de ce type, comportant l'élimination statistique des effets de la directivité du transducteur des échos reçus sur un transducteur à simple faisceau, est alors décrite. Les détails de l'application de cette technique à la mesure des indices de réflexion de merlans bleus et de sprats sont décrits et les résultats de ces mesures, accompagnés d'estimations de précision et d'exactitude, sont discutés.

1. INTRODUCTION

In order to convert acoustically derived distributions of a fish species into area densities and hence population estimates it is essential to have accurate estimates of fish target strengths. At present these are principally obtained from experiments involving stunned or caged fish but it has been shown that fish behaviour and physiology significantly influence the observed target strength. Such parameters cannot presently be measured for wild fish and hence it is difficult to extrapolate from the target strength results obtained under controlled experimental conditions to those which may apply during a particular acoustic survey.

One possible solution to these problems lies in *in situ* measurement of fish target strength but in order to achieve this aim it is necessary to be able to remove the effects of transducer directivity from the received echoes. This can be done either directly by equipment which can determine a fish's position within an acoustic beam (Dunn, 1977; Ehrenberg, 1974) or indirectly by statistical manipulation of the received echoes on a conventional echosounder transducer (Craig and Forbes, 1969; Midttun and Nakken, 1971; Ehrenberg, 1972). Such indirect techniques are attractive as they require only minor modification to existing acoustic survey equipment. However, a complete solution to the statistical problems has not been reported and consequently few experiments have been attempted on live fish. This paper describes a technique which is capable of accurately determining the target strength of fish under certain limited conditions. In practice these conditions have not proved restrictive and results of experiments performed upon sprat and blue whiting are presented.

2. *In situ* MEASUREMENT TECHNIQUE

The essential prerequisites to *in situ* measurement are that individial fish echoes can be resolved and that a representative sample of these fish can be caught for species and size determination. Fish samples obtained by trawling have largely unknown sampling efficiencies both between species and size groups. It is therefore essential to attempt to conduct both acoustic surveys and in situ target strength measurements when the fish occur in near monospecific conditions.

For most pelagic species, the requirement for isolating single fish echoes can often only be met when the fish disperse at night or are on the edges of large concentrations. These are also the conditions when species mixing (e.g. with predators or prey) are most likely and hence great care must be taken to adequately sample the population. In these low density aggregations it is conceivable that the fish behaviour and/or physiology (e.g. fish performing diurnal migration) may be different to that occurring in higher density daytime shoals. The experimental data to confirm this hypothesis are not available, indeed it is likely that such data could only be obtained from in situ measurements made with high resolution equipment.

Having located and sampled a suitable low density fish aggregation the survey transducer is lowered to within 10 to 20 m of the fish in order to maximise its resolution capability. Simulation studies have shown that in excess of 10 000 single fish echoes must be analysed if an unbiased estimate of the mean target strength is to be obtained. The time taken to collect his amount of data is dependent upon fish density, but between twenty minutes one hour has proved typical for sprat distributions. Whilst this can most easily be accomplished by allowing the ship to drift with the fish aggregation, the target strength distribution so obtained may not be applicable to survey conditions. Olsen (1979) has observed that herring may react to ship's noise and in so doing influence their perceived target strength. In order to determine whether these observations are typical for pelagic fish it is necessary to perform in situ measurements whilst the vessel is at normal survey speed. Such experiments have been successfully undertaken with sprats but only when the fish aggregations were extensive and as far as could be ascertained, homogeneous.

3. COLLECTION OF SINGLE FISH ECHOES

The transducer used to collect fish echoes was designed by my former colleague H.R. Stewardson and has an elliptical beam pattern switchable between approximately 9° by 14° and 9° by 4°. This is calibrated by means of the technique described in Robinson and Hood (1982). Received echoes are processed in a Time Varied Gain amplifier (Hoare, 1978) and a precision rectifier with a combined calibration accuracy of better than ± 0.25 dB over a 50 dB output dynamic range.

Single fish echoes are selected from the rectified signals by means of a microprocessor controlled system which has been outlined in Robinson (1978). In an attempt to ensure that few multiple echoes are arroneously accepted as single fish echoes the adopted selection criteria are rigorous. This does, however, result in a large percentage of received echoes being rejected in high density aggregations. After echo selection, the microprocessor produces a histogram of echo intensities which, when smoothed, provides the input data for the target strength analysis program.

4. THE ECHO ANALYSIS TECHNIQUE

After correction for propagation losses, a received echo intensity is the product of a fish's location within the acoustic beam and its target strength. Since individual fish positions within the beam are unknown, this situation can only be described in a probabilistic manner. The echo intensity probability density function (PDF) is therefore the result of convolving the fish target strength PDF with the beam function PDF, (this being the joint PDF of a fish's location in space and the transducer directivity function). This has been mathematically formulated by Ehrenberg (1972) and may be written:

$$P_I(I) = C \int_0^{T_{max}} P_T(t)\, P_B(I/t)\, dt \quad I \geq \text{Threshold}$$

where $P_I(I)$ is the measured echo intensity PDF

$P_T(t)$ is the unknown target strength PDF
$P_B(I,t)$ is the calculable beam function PDF assuming a uniform fish density distribution.
T_{max} is the largest expected target strength and C is a normalising constant.

Theoretically the unknown target strength PDF may be recovered by deconvolution. One technique for the solution of this equation is described in Robinson (in press) and consists of subdividing the unknown density function $P_T(t)$ into a number of intervals. Low order polynomials (maximum order 3) are fitted to each subsection, subject to the constraint that the function value and first derivative are continuous at each data boundary. The unknown polynomial coefficients may then be determined simultaneously by a least squares minimisation. Tests with simulated data have shown that unimodal target strength PDFs with standard deviations less than 2.5 dB can be reconstructed to an accuracy of approximately ± 0.5 dB. For distributions with larger standard deviations the equations to be solved become increasingly ill-conditioned and the algorithm produces underestimates of the mean target strength. This effect would not normally be overlooked as the extracted target strength PDF adopts characteristic features once numerical instability becomes a serious problem.

5. RESULTS

Results of the application of this technique to blue whiting are described in Robinson (1982). The fish were located off the west coast of Scotland at a depth of approximately 300 m. Their mean length was 31.1 cm from which their mean weight was calculated to be 139 g. At the time of this experiment, the acoustic calibration reference was a table tennis ball. Recent measurements on such balls by Dunn (Paper 89 at this meeting) have produced a revised figure for their target strength at 30 kHz. When this correction is applied to the blue whiting data their estimated target strength becomes -33.5 dB/kg ± 1.0 dB.

The calibration of the survey equipment is no longer referenced to table tennis balls and is now considered to be accurate to better than ± 0.5 dB (Robinson and Hood, 1982). The results of an experiment performed on sprat off the south-west coast of England in December 1981 are shown in Figs 1 and 2. The echo recordings were made at night whilst the fish were in a dispersed layer approximately 15-30 m deep, with the ship steaming at 5.5-6 knots. The fish were sampled with an 800 mesh Engels trawl with a 10 mm lining in the codend. The resultant target strength is -28.9 dB/kg for fish of mean length 12.6 cm and weight of 15 g. A similar experiment conducted in the Inner Silver Pit in January 1980 save a mean target strength of -27.2 dB/kg for sprat of mean length 7.15 cm and weight 2.3 g. These data were obtained at night whilst the fish were in a dispersed layer 20-40 m deep. They were again sampled with an 800 mesh Engels trawl.

A consideration of the potential errors in the analysis procedure indicates that these target strength estimates are accurate to ± 0.7 dB (this excludes any bias due to the sampling efficiency of the trawl).

A large amount of additional sprat data has not yet been analysed. These data include recordings made at greater depths and with fish of differing mean lengths.

6. DISCUSSION OF RESULTS

The only source of published data on the target strength of either sprat or blue whiting known to the author is Nakken and Olsen (1977). The authors provide equations for maximum dorsal aspect target strength which must then be corrected for observed fish behaviour to give the mean target strength. For gadoids, the authors suggest that the mean target strength will be 8-9 dB lower, whereas for herring they suggest a 6 dB reduction. (No figure for the correction of the sprat data is provided). If the resulting data are converted from target strength per fish to that per kg, the following comparisons with the in situ results are obtained:

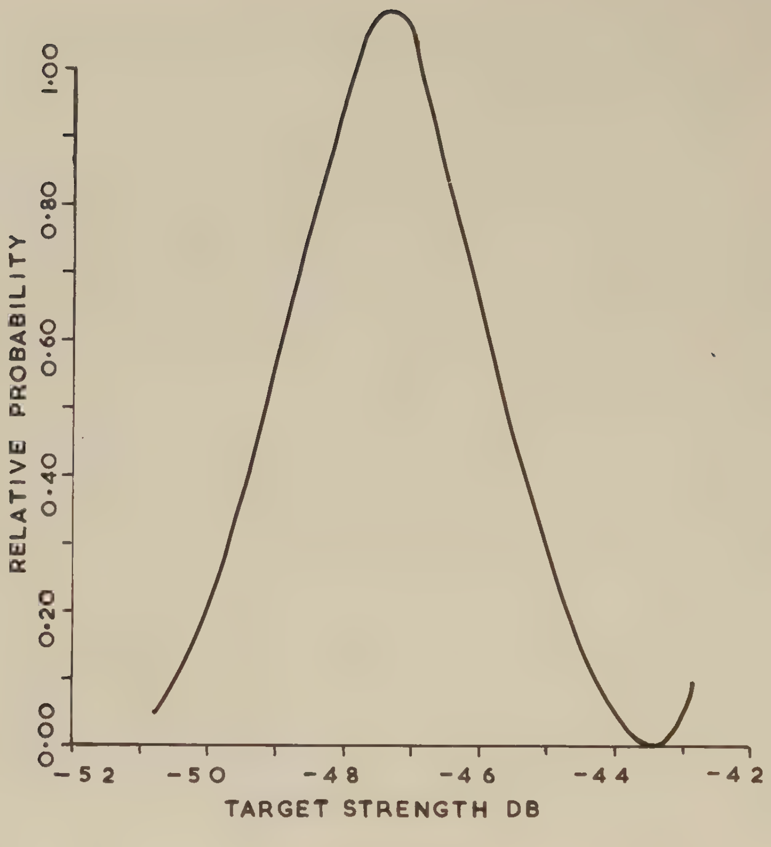

Fig. 1. The extracted sprat target strength distribution.

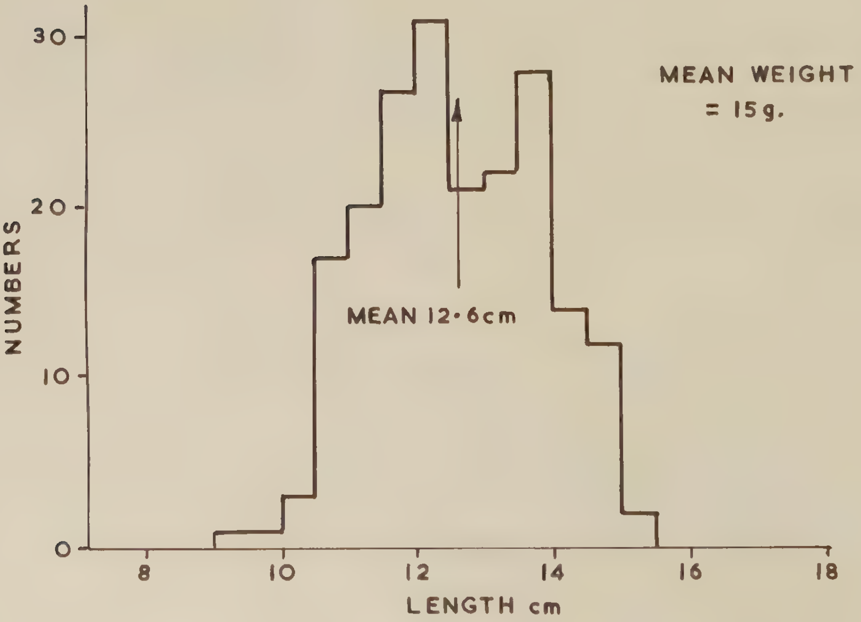

Fig. 2. The sprat length distribution.

SPECIES	LENGTH	WEIGHT	TARGET STRENGTH db/kg	
			in situ	Nakken & Olsen
Blue whiting	31.1	139	-33.5	-33.0 (approx)
Sprat	12.6	15	-28.9	-29.6
Sprat	7.15	2.3	-27.2	-25.7

The Nakken and Olsen data were obtained from stunned fish at 38 kHz and it is not known how applicable they are to free swimming fish at 30 kHz. Nevertheless, they are interesting for comparative purposes.

The *in situ* sprat results do appear to display a length dependence but no conclusions can be drawn until more experimental data have been processed.

7. CONCLUSIONS

An *in situ* technique has been developed which is capable of recovering unimodal target strength PDFs with standard deviations less than 2.5 dB from the received echoes of a conventional echosounder transducer. Work is in hand to ascertain whether these limitations can be reduced but the technique has nevertheless proved adequate for target strength data on sprat and blue whiting to be produced.

SUCCESSES WITH CONVENTIONAL *IN SITU* DETERMINATIONS OF FISH TARGET STRENGTH

by

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ABSTRACT

For reasons of poor statistics, and the frequent failure to appreciate this, the Craig and Forbes' algorithm (1969) is sometimes distrusted. To show the basic reliability and power of the method, acoustic data on several freshwater species are analysed. These were gathered at 70 kHz with a SIMRAD EY-M echo sounder, analysed for single fish echoes, and further treated without purging of any kind. The results are correlated strongly and unambigously with trawl data, thus allowing specification of *in situ* target strength.

RESUME

L'algorithme de Craig et Forbes (1969) est parfois mis en doute. La raison en est que les statistiques sont insuffisantes et que ce fait est fréquemment ignoré. Nous analysons ici les données acoustiques concernant plusieurs espèces de poissons d'eau douce pour apprécier l'exactitude et l'efficacité de la méthode. Ces données ont été recueillies à 70 kHz, à l'aide d'un écho sondeur Simrad EY-M. L'analyse se base sur les échos de poissons isolés étudiés sans aucune correction. Les résultats ainsi obtenus sont mis très strictement en corrélation avec les données de chalutage et permettent la détermination *in situ* des indices de réflexion.

1. INTRODUCTION

In Norway there has been an increasing use of hydro acoustic techniques in monitoring freshwater fish stocks. Due to a newly developed portable echo sounder system it has been possible to do acoustic work even in small lakes.

It appears to be easy to obtain good singlefish echoes from pelagic freshwater species like Whitefish (*Coregonus lavaretus*), Smelt (*Osmerus eperlanus*), and Vendace (*Coregonus albula*). By contrast to many marine species they are little influenced by the noise produced by the survey boat.

This rather ideal situation for acoustic work has made it possible to apply the simple algorithm proposed by Craig and Forbes (1969) to remove the effect of the beampattern from the received echo distribution. It statistically corrects the echo strength distribution to a target strength, TS, distribution.

The great advantage of this method is its ability to work with conventional transducers and echosounders. The drawback is that it assume the fish to be uniformly distributed within the samplevolume, which is often not the case.

Former work by Traynor (1975) and Ehrenberg (1979) has discussed these problems in detail and recommended that dual beam or split beam systems should be used for directly measuring the target strength of fish. However, when observing scattering layers with good resolution of single fish echoes the Craig and Forbes' indirect extraction techniques for *in situ* target strength measurements can show good results, and the target strength distribution will mirror the actual fish length distribution found in trawl catches.

This paper will demonstrate the power of the method and will perhaps encourage biologists to use existing echosounder systems to get more information from single fish echoes found in a scattering layer. On most research vessels it is possible to connect a small computer to the scientific echosounder and to use the Craig and Forbes algorithm to find the mean target strength of the observed fish. Together with an echointegrating program this can be of great help when assessing total biomass of fish in a scattering layer.

2. MATERIALS AND METHODS

2.1 The method

By using an echosounder with an 40 log R time varied gain control, TVG, the received echosignals are independent of range. The echo amplitude depends only on the angular coordinates of the target. The directivity pattern of the system is obtained by combining the transmit and receive directivity from the transducer. In these examples the directivity pattern was divided in 2 dB class intervals.

The basic idea behind the algorithm is that the received echosignals with the highest intensity (N_1) must come from the biggest fish located within the central part of the acoustic beam, class interval A_1. The second highest echointensities, N_2, must come from the second biggest fish located in class interval A_1, plus the biggest fish located in class interval A_2 and so forth:

$$N_1 = d_1 \cdot A_1$$
$$N_2 = d_2 \cdot A_1 + d_1 \cdot A_2$$
$$\cdot$$
$$\cdot$$
$$N_n = d_n \cdot A_1 + \ldots\ldots + d_1 \cdot A_n$$

where

N_1 .. N_n = number of echoes received within each class interval.

d_1 .. d_n = fish densities within each size category.

A_1 .. A_n = areas given by the directivity pattern.

When solving these equations the true fish densities d_1 .. d_n can be calculated. All negative density values are set equal to zero.

2.2 The echosounder system

All data have been gathered with a SIMRAD EY-M scientific echosounder working at 70 kHz.

This is a portable battery operated system weighing only 10 kg, designed to operate from small boats. The echosignals are shifted down from 70 kHz to 10 kHz at the calibrated signal output, which makes it possible to record the analog signal on an ordinary high fidelity tape recorder. During these experiments all data have been recorded with a 40 log R, time varied gain control, TVG, applied to the echosounder preamplifier. The analog echosignals have been recorded on a Nakamichi 550 tape recorder.

2.2.1 The transducer

SIMRAD has developed a multi-element ceramic transducer to the EY-M sounder. It is a narrow beam transducer with a circular beam pattern. On the actual transducer used, the beam angle was measured to 11.2 degrees at the -3 dB level. By substituting this angle in the theoretical directivity function $b(\theta)$ for a circular transducer the

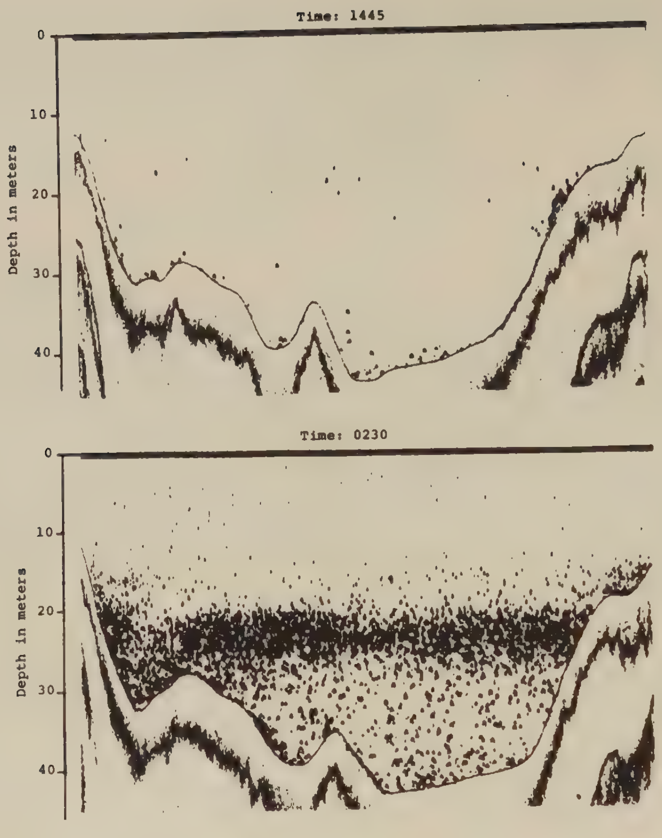

Fig. 1. Echograms from the trawling area in Konnevesi. Notice the day - night migration of vendace and smelt. All work was done after dark when the fish spread out in the pelagic zone.

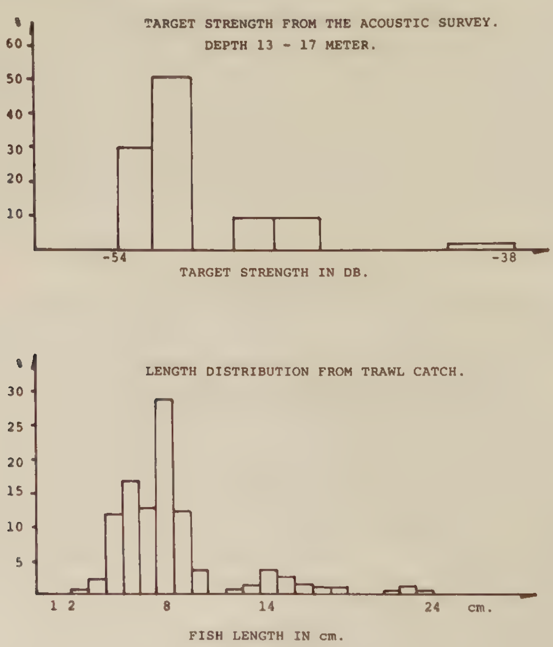

Fig. 2. Percentage length frequency histogram from trawl hauls 3 and 4 on September 5-6, 1980 (lower) and target strength histogram from the acoustic survey on the same date.

effective diameter was found. From this the directivity pattern was determined, and the beam split in ten 2 dB classes.

The transducer was mounted to a V-fin and suspended about 0.5 meter from the side of the boat. It was towed at a depth of 1 meter. This form of mounting is preferable when operating from small boats. It gives the transducer a good stability in the water and it is easy to move it away from noise sources like motor and propeller.

2.3 Data acquisition system

The echoamplitudes are reproduced from the recorded 10 kHz analog signal in an AC/DC converter and the envelope sampled every 0.1 millisec. by a 8 bit analog to digital converter.

The digital signals are stored on floppy disks by a Mostek FLP-80, Z-80 based, micro computer. The same computer is used when running the algorithm.

2.4 Survey areas

Two lakes have been investigated by echosounder and pelagic trawling at the same time, lake Mjøsa, Norway and lake Konnevesi, Finland. Mjøsa, the biggest lake in Norway, has a surface area of 362 km^2 and a mean depth of 153 m. The testfishing with pelagic trawl was a part of a biological program run by The Norwegian Department of Fish and Game.

Konnevesi, Finland, has a surface area of 188 km^2, a mean depth of 7.5 meter and a max depth of 56 meter. In this lake the whole exercise was carried out by The European Inland Fisheries Advisory Commission, EIFAC. Bagenal *et al*. (1982).

3. RESULTS

3.1 Lake Konnevesi

The exercise in Konnevesi took place from 1 to 10 September 1980. The max. depth in the trawl area was 44 meter and echograms from the transect line are shown in Fig. 1. All work was done after dark when the fish spread out in the pelagic zone. To get some information of the precision of the echo survey estimate two runs were made as near as possible over the same transect. The second run was completed within 30 min. of the first run. Between the time 2200 and 2300 the 14th of November 1980 the following data were recorded in Furnesfjorden, Mjøsa:

Number of fish per hectare in two replicate runs.

Depth	Run 1	Run 2	Diff. from mean
4- 8 meter	118	140	8.5%
8-10 meter	396	449	6.3%
10-23 meter	1472	1484	0.4%

The sampling was done by a two-boat mid-water trawl. Two different types of trawl were used. A commercial vendace trawl, and a young fish trawl. The catch from the two trawls were combined to get the best representation of the fish length distribution. Only the deep water trawl catches and acoustic survey data have been used to minimize the bias from scaring the fish by the boats. The percentage length frequency histogram from trawl hauls and the target strength histogram from the acoustic surveys are shown in Figs. 2, 3 and 4.

3.2 Lake Mjøsa

Like in Konnevesi, two replicate runs were made to look at the precision of the echo survey estimate. The two runs were made as near as possible over the same tran-

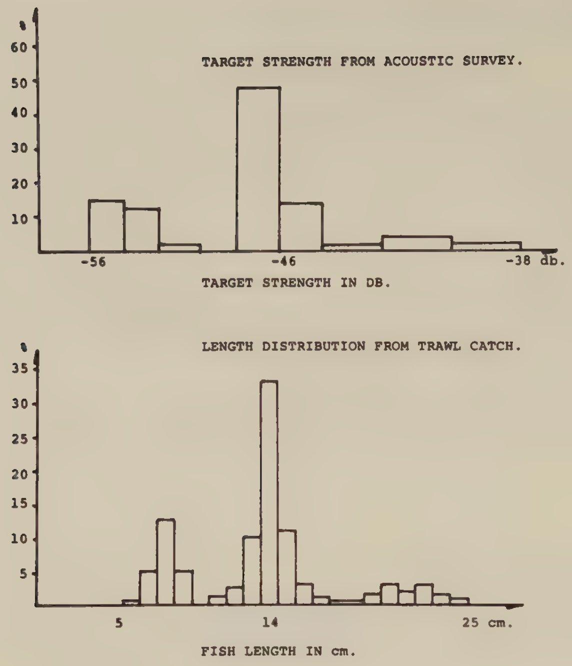

Fig. 3. Percentage length frequency histogram from trawl hauls 6 and 8 on 7-8 September 1980 (lower) and target strength histogram from the same date and at the same depth, 16-20 m.

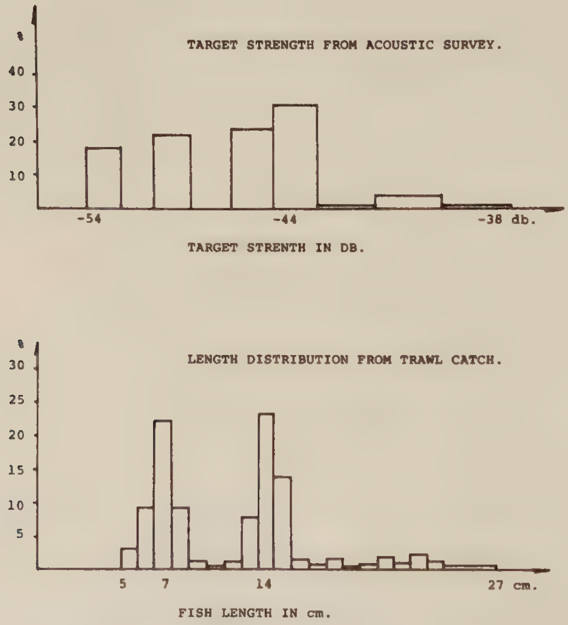

Fig. 4. Percentage length frequency histogram from trawl hauls 12 and 13 on 8-9 September 1980 (lower) and the target strength histogram from the same date and the same depth, 16-20 meter.

Table 1.

Echodistribution from 5 - 15 meter in Furnesfjorden.

TS(dB):		Echonumber:	Calculated density:	
A_1	-38	4	15	fish/hectare
	-40	4	1	"
.	-42	6	8	"
.	-44	5	0(neg.)	"
.	-46	16	41	"
.	-48	24	33	"
.	-50	45	83	"
.	-52	62	72	"
.	-54	96	141	"
A_{10}	-56	65	0(neg.)	"

Table 2.

Echodistribution from 15 - 39 meter in Furnesfjorden.

TS(dB):		Echonumber:	Calculated density:	
A_1	-38	50	41	fish/hectare
	-40	91	35	"
.	-42	96	7	"
.	-44	186	76	"
.	-46	317	113	"
.	-48	320	13	"
.	-50	555	201	"
.	-52	555	18	"
.	-54	798	218	"
A_{10}	-56	386	0(neg.)	"

Table 3.

Echodistribution from 30 - 45 meter in Furnesfjorden.

TS(dB):		Echonumber:	Calculated density:	
A_1	-38	21	6	fish/hectare
	-40	35	5	"
.	-42	43	3	"
.	-44	70	9	"
.	-46	291	69	"
.	-48	363	26	"
.	-50	609	81	"
.	-52	601	4	"
.	-54	834	80	"
A_{10}	-56	437	0(neg.)	"

Table 4.

Echodistribution from 45 - 60 meter in Furnesfjorden.

TS(dB):		Echonumber:	Calculated density:	
A_1	-38	2	0	fish/hectare
	-40	9	1	"
.	-42	10	0	"
.	-44	70	10	"
.	-46	265	65	"
.	-48	605	26	"
.	-50	916	55	"
.	-52	931	8	"
.	-54	1209	52	"
A_{10}	-56	695	0(neg.)	"

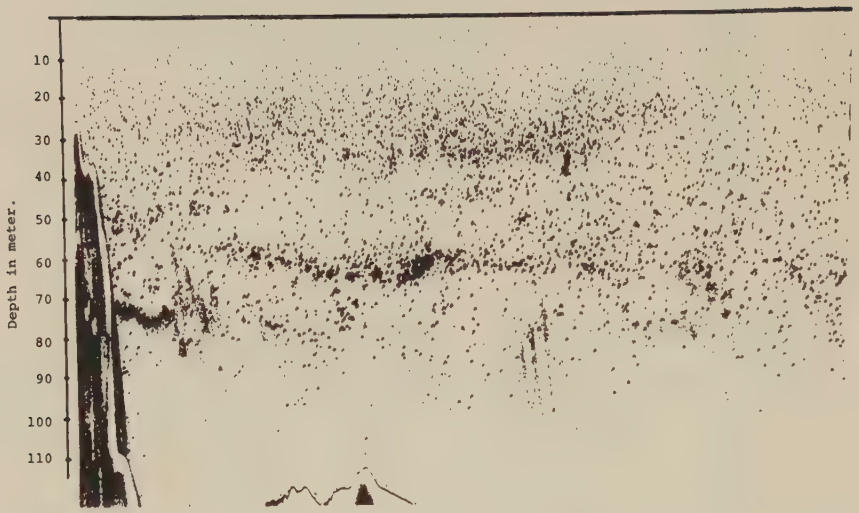

Fig. 5. Echogram from the trawling area in Furnesfjorden, Mjøsa.

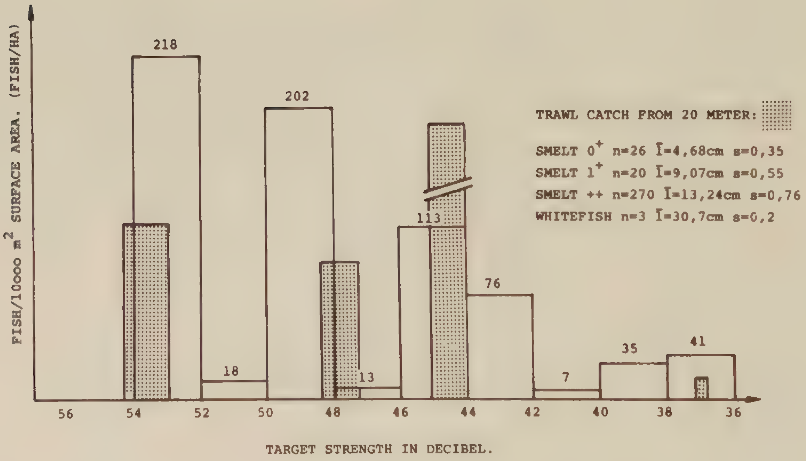

Fig. 6. Analysis of single fish echoes in Furnesfjorden, Mjøsa.
Depth: 15 - 30 meter. Echocounts: 3354.

ACKNOWLEDGEMENTS

Thanks to the staff from the Norwegian Department of Fish and Game, The Finnish Game and Fisheries Research Institute and T.B. Bagenal, The Freshwater Biological Association, England, without whose help these experiments could not have been done.

sect. The second run was completed within 60 min. of the first run. Between the time 2200 and 2300 the 14th of November 1980 the following data were recorded in Furnesfjorden, Mjøsa:

Number of fish per hectare in two replicate runs:

Depth	Run 1	Run 2	Diff. from mean
10-30 meter	2266 fish/ha.	2467 fish/ha.	8.5%
30-60 meter	1611 fish/ha.	1639 fish/ha.	1.7%
60-80 meter	406 fish/ha.	429 fish/ha.	5.5%
Total density	4283 fish/ha.	4535 fish/ha.	5.7%
Total number of echoes analysed:	13189 echoes	12185 echoes.	

An echogram from the trawl area in Furnesfjorden is shown in Fig. 5. The echo survey was carried out 30 min. before trawling.

4 depth layers were analysed: 5-15 meter, 15-30 meter, 30-45 meter and 45-60 meter.

The results are listed in table 1 through 4. When the echo number in a depth layer was bigger than 1000, no negative density values were detected when solving the set of equations.

The trawl was towed at a depth of 15-20 meter for 30 min.

The catch:

0+ smelt	mean length	4.7 cm	s = 0.4 cm	n = 26
1+ smelt	mean length	9.1 cm	s = 0.6 cm	n = 20
++ smelt	mean length	13.2 cm	s = 0.8 cm	n = 270
++ whitefish	mean length	30.7 cm	s = 0.2 cm	n = 3

Due to 15 mm mesh in the trawl cod end, the catch of 0+ and 1+ of smelt would not be representative for the actual fish density. However, the length distribution of these yearclasses could be established. Fig. 6 shows how these length groups correspond to target strength classes. By making a forced fit of the -45dB TS class to the 13 cm smelt I got a formula (1) giving an approximate relation between target strength, TS, and fish length (l) in cm.:

$$TS = 20 \log_{10} l - 67 \qquad (1)$$

4. DISCUSSION

The experiments in lake Mjøsa and lake Konnevesi show that the Craig and Forbes algorithm and trawl catches can give size frequency results which are in good agreement.

It is important to remember that the conditions were close to ideal. When using this method in assessing fish populations in lakes, it is necessary to wait until the fish is located in a uniform scattering layer in deep water. (Below 10 meter). The speed of the survey boat should be relatively slow and the puls repitition rate of the echosounder high. This will secure enough echoes to run the algorithm. If possible the number of single fish echoes should be higher than 1000. The best results will be obtained when successive echoes can be received as the fish is passing through the beam.

TARGET STRENGTH MEASUREMENTS OF WALLEYE POLLOCK (THERAGRA CHALCOGRAMMA) AND A SIMULATION STUDY OF THE DUAL BEAM METHOD

by

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ABSTRACT

Dual beam target strength data were collected on walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea in June and July of 1979. Nighttime target strength estimates ranged from -27.0 to -32.9 dB per kilogram for pollock with mean lengths from 16 to 48 cm (0.03 to 0.64 kg). Average target strength estimates at night were approximately 3 dB less than those obtained during the day. Possible causes of this difference are discussed. The results illustrate the need to obtain behaviour-specific *in situ* target strength estimates for accurate scaling of echo integrator data.

Results of a comprehensive simulation of dual beam data collection and analysis are also reported. The simulation, which was carried out over a range of target densities, included formation of echo returns from each individual fish within the beam, their superimposition, the addition of noise at the transducer face, the filtering that occurs within the receiving system, sampling of the resultant waveform, and the acceptance of echoes as being from single fish on the basis of pulse length. The effects of density, signal to noise ratio, and the choice of pulse length acceptance window on error in the estimation of the mean scattering cross section using the dual beam technique are discussed.

RESUME

Les données concernant l'index de réflexion obtenu à partir d'un transducteur à double faisceau ont été recueillies sur les morues du Pacifique occidental (*Theragra chalcogramma*) dans l'est de la mer de Bering en juin et juillet 1979. La nuit, les évaluations de l'index de réflexion s'étendent entre - 27,0 et - 32,9 dB/kg pour les morues du Pacifique occidental pour des longueurs moyennes de 16 à 48 cm (0,03 à 0,64 kg). Les évaluations de la moyenne des indices de réflexion durant la nuit étaient approximativement de 3 dB de moins que celles obtenues durant le jour. Les causes possibles de cette différence sont en discussion. Les résultats illustrent le besoin d'obtenir des estimations des index de réflexion pour chaque type de comportement pour arriver à une gradation précise des données de l'écho-intégrateur.

Les résultats d'une simulation exhaustive de la collecte et de l'analyse des données provenant d'un transducteur à double faisceau sont aussi rapportés. La simulation, qui a été réalisée pour un éventail de densités de cibles concernait la formation des échos de chaque poisson individuel au sein du faisceau, leur superposition, l'addition d'un bruit au niveau de la surface du transducteur, le filtrage qui se produit au sein du système récepteur, l'échantillonnage de l'onde résultante, et l'acceptation des échos comme provenant d'un poisson isolé sur la base de la durée de l'impulsion. Les effets de la densité, du rapport signal/bruit et du choix de la fenêtre de tolérance de la durée de l'impulsion sont discutés.

1. INTRODUCTION

1.1 Background

Knowledge of the acoustic back-scattering properties of a fish population is necessary to estimate absolute abundance by means of echo integration (Midttun and Nakken, 1971; Ehrenberg and Lytle, 1977). Target strength to length relationships have been developed for some species from measurements of tethered fish (e.g., Love, 1971; Nakken and Olsen, 1977; Buerkle and Sreedharan, 1981) and from cage experiments on untethered fish (e.g., Goddard and Welsby, 1977). Many investigators (e.g., Johannesson and Losse, 1977: Burczynski, 1981) have indirectly measured the back-scattering properties of fish enclosed in a cage by integrating a known density of fish and empirically determining the integration scaling constant. The problem in applying the results of controlled experimental studies is that it is difficult to determine how representative the fish in the controlled situation are of those in their natural environment. Differences in fish behaviour or the physiological state of the fish between the controlled and survey situations will result in changes in the back-scattering properties of the fish. Of particular importance is the tilt angle distribution. Because fish are highly directional scatterers, relatively small differences in orientation result in large changes in target strength. An additional complication is the effect of changes in fish depth on the back-scattering strength of the swim bladder for vertically migrating fish with closed swim bladders. Following a rapid change in fish depth, the time required to restore the swim bladder to its original volume (by gas absorption or secretion) may be very long and is probably quite variable. Little detailed information is available about the behaviour of fish populations, making it difficult to relate target strength measurements of the artificially constrained fish to the free-swimming fish population target strength parameter. An obvious, and theoretically more appealing, alternative to controlled experiments is the measurement of the target strength characteristics of a fish population in situ.

A problem with in situ techniques is that echo ampilitude (E) is a function of not only the scattering cross section[1] (σ) of the individual fish but also the directivity of the beam at the angular coordinates of the fish, $b(\theta,\phi)$,

$$E^2 = K\, b^2(\theta,\phi)$$

where K is a constant, dependent on echo sounder system parameters. Indirect techniques which attempt to statistically remove the beam pattern effect (e.g., Craig and Forbes, 1969; Ehrenberg et al. 1980) have been used but often perform poorly. The dual beam method, a direct in situ target strength measurement technique, removes the beam pattern effect directly from each received single target.

This paper describes dual beam target strength measurements of walleye pollock (Theragra chalcogramma) made in the eastern Bering Sea. In addition, results of a comprehensive simulation analysis of the dual beam system describing the effects of signal to noise ratio and fish density on error in the dual beam method are presented.

2. DUAL BEAM TARGET STRENGTH MEASUREMENT METHOD

The dual beam target strength measurement method was first proposed by Ehrenberg (1974). The method and its use have been described by Ehrenberg et al. (1976), Ehrenberg (1978a and 1979), Traynor and Ehrenberg (1979), and Traynor and Nelson (1981). The technique utilizes a transducer with axially aligned narrow and wide beams. Sound is transmitted on the narrow beam, and returning fish echoes are received simultaneously on both the narrow and wide beam channels. For single fish targets, the narrow beam directivity, $b_n(\theta,\phi)$, can be estimated as a ratio of the intensities (I) in the narrow and wide beam:

$$\hat{b}_n(\theta,\phi) = I_n/I_w$$

and the scattering cross section, σ, can be estimated as

$$\hat{\sigma} = K\, I_w^2/I_n$$

where K is a constant dependent on system calibration parameters.

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[1] Target strength is defined as $10 \log_{10} (\sigma/4\pi)$.

A problem with any in situ target strength estimation procedure is the bias against smaller targets inherent in acoustic data collection and processing systems. This bias results from a dynamic range limitation imposed by background noise conditions, noise characteristics of the system, and the single target recognition algorithm. That is, a single target must exceed a voltage threshold level, T_n, to be accepted for target strength analysis. Due to this threshold, only fish with large scattering cross sections will be detected in the low directivity portion of the narrow beam pattern, resulting in discrimination against small targets. This bias can be reduced by imposing a beam pattern threshold, T_b, requiring that $\hat{b}_n(\theta,\phi)>T_b$.

3. TARGET STRENGTH MEASUREMENTS OF WALLEYE POLLOCK

3.1 Methods

Dual beam target strength measurements of walleye pollock and associated midwater trawl catch data were collected in the eastern Bering Sea during June and July of 1979. The work was conducted on the NOAA ship "Miller Freeman", a 66 m, 2,200 hp stern trawler. Data were collected in the Aleutian Basin near Adak Island and at two locations north of the Pribilof Islands on the continental shelf (Fig. 1): In the Aleutian Basin area, the fish could be resolved as single targets during both day and night. On the continental shelf, fish usually could not be detected as single targets during the day and therefore, data were collected only at night.

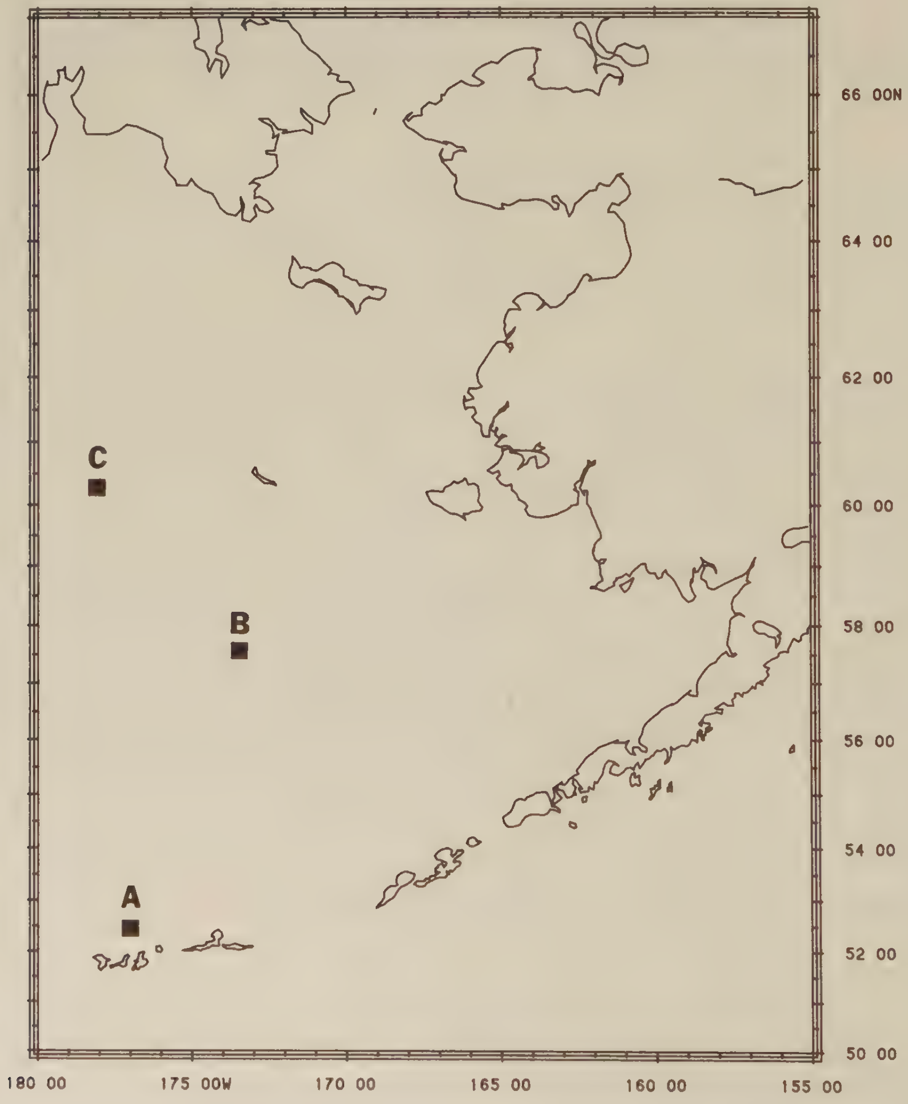

Fig. 1. Locations of target strength data collection over the Aleutian Basin (A) and eastern Bering Sea continental shelf (B and C).

The target strength measurements were obtained using a 38 kHz echo integration system described by Traynor and Ehrenberg (1979) and by Traynor and Nelson (1981). The transducer was mounted in a V-fin towed at a depth of 20 m and an average speed of 5 knots during target strength data collection. System calibration techniques are presented in detail by Traynor and Nelson (1981). System specifications and calibration data obtained prior to and after the data collection period are shown in Table 1. The system's transmitted pulse length was 0.6 ms. The average half amplitude pulse width of the received filtered echoes from well defined single targets was only ∿0.5 ms. All echoes with half amplitude pulse lengths of 0.4 to 0.6 ms were classified as single targets. The 0.2 ms window was chosen on the basis of empirical observations of the range in half amplitude pulse lengths in a very low density situation. This acceptance window contained over 95% of the observed targets. Analyses of simulation data presented elsewhere in this paper support the choice of this window to minimize error in the estimation of $\bar{\sigma}$.

Table 1. Basic echo sounder system specifications and calibration data.

Specifications		Calibration data		
Frequency	38 kHz	Calibration date	8/22/79	10/4/79
		Water temperature (°C)	21.5	18.3
Transducer		Source level (dB//1μpa at 1m)	223.9	224.4
Dimensions	44 cm, circular			
Material	barium titanate	Transducer (narrow beam) transmitting sensitivity (dB μpa/V at 1m)	171.9	172.2
Beam width (between -3 dB pts.)				
Narrow beam	6°			
Wide beam	25°	Transducer receiving sensitivity (dBV/μpa)		
Directivity index		Narrow beam	-171.6	-175.9
Narrow beam	26.7 dB	Wide beam	-174.2	-174.1
Wide beam	18.2 dB			
Transmitter		Receiver (TVG amplifiers)		
Type	Instruments, Inc. (Model SPG-4B)	Narrow beam (20 logR + 2 α R)	Ithaco (custom design)	
Nominal power output	1 kw and 5 kw	Narrow beam (40 logR + 2 α R)	Ithaco (custom design)	
Nominal pulse length	0.6 ms	wide beam (40 logR + 2 α R)	Ithaco (custom design)	
Pulse repetition rate	60/min (selectable, 1-99/min)			
TVG control Digital	Echo recorder EPC 19-inch recorder	Towed V-fin Edo-Western Model 6315		
Towing cable (faired)	2 cm; 13 conductors			

To minimize the acceptance of noise as fish targets, only targets that exceeded the root mean square (RMS) noise level by a factor of two were included in the analysis. To reduce the bias against small targets caused by the noise threshold, targets with a beam pattern directivity estimate, $\hat{b}_n(\theta,\phi)$, less than -3 dB were excluded from analysis. This beam pattern threshold was chosen on the basis of simulation studies, described later in this paper, which indicated that a threshold value of about -3 dB minimized error for most simulated fish populations and noise situations.

Sampling of fish echo sign was done with a rectangular midwater trawl (Norsenet, Ltd., Norway[2]) fixed with 6 m^2 Waco doors and 75 m bridles (two per side). Mesh sizes in the trawl ranged from 1000 mm stretched measure forward to 46 mm in the cod end which was covered with a double braided bag with a mesh size of 144 mm. The trawl was positioned with a 30 kHz Elac cable netsounder system. Netsounder records indicated that the net's vertical mouth opening ranged from 18 to 20 m, depending upon trawling speed and the amount of trawl cable set out. Trawling speed varied from 2 to 3 knots.

On trawl haul was made by the "Syotoku Maru" No. 35, a vessel under contract to the Japanese Far Seas Fisheries Laboratory. The midwater trawl had a vertical mouth opening of about 28 m. Net mesh sizes ranged from 400 mm stretch mesh forward to 100 mm in the cod end.

Approximately 200 pollock were randomly sampled from each haul to determine length composition. Fork lengths were measured to the nearest centimeter. About 100 fish in this sample were randomly subsampled to obtain individual weight data. Weights were measured to the nearest gram.

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[2] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

3.2 Results

Eight samples of target strength measurements were obtained. These included six samples from the Aleutian Basin and two from the continental shelf. Five midwater trawl hauls (Table 2) were made to identify the species and size composition of insonified targets. The catch in each haul was composed almost entirely of walleye pollock.

Table 2. Midwater trawl catch data.

							Catch			
						Headrope	Walleye pollock		Other species	
Haul	Vessel[1/]	Date	Time	Position		depth(m)	Wt(kg)	No.	Wt(kg)	No.
1	SM	6/11/79	2119-2219	52°44.0'N	176°50.0'W	50	73	115	--	--
2	MF	6/12/79	1300-1500	52°43.9'N	177°11.4'W	51	111	160	--	--
3	MF	6/13/79	0003-0203	52°44.2'N	177°16.5'W	55	58	78	< 1	8(squid)
4	MF	7/13/79	0230-0252	57°55.6'N	173°44.5'W	64	233	2,583	--	--
5	MF	7/22/79	0259-0354	60°26.5'N	178°06.8'W	49	161	1,808	< 1	1(skate)

[1/] SM = Syotoku Maru No. 35 MF = Miller Freeman

The results of the target strength measurement data analysis are shown in Table 3. In the Aleutian Basin area (samples 1-6), adult pollock were observed in monospecific, low density aggregations, and most fish were detected as single echoes during both night and day. For measurements were during the day (samples 1, 3, 4, and 5 combined), the target strength of the mean scattering cross section was -29.9 dB/kg, whereas measurements made at night (samples 2 and 6 combined) had a mean value of -32.7 dB/kg. Mean depth of accepted single targets in the 50-85 m depth region analyzed were 67.2 and 71.1 m for night and day, respectively.

Table 3. Target strength measurements of walleye pollock in the Bering Sea. For comparison purposes, target strength analyses were restricted to depths of 50-85 m for all samples.

					Mean fish						
Sample	Location/ Period[1/]	Date	Collection time	Associated haul	Length(cm)	Wt(g)	$\bar{\sigma}$	S.D.($\bar{\sigma}$)	TS($\bar{\sigma}$) (dB/ fish)	TS($\bar{\sigma}$) (dB/ kg)	Sample size
1	B/D	6/11/79	1735-2109	1			.00854	.00038	-31.67	-29.73	1,555
2	B/N	6/12/79	0136-0436	1	47.7 (S.D.=2.0)	[2/]	.00408	.00056	-34.80	-32.94	563
3	B/D	6/12/79	0540-0834	2			.00913	.00040	-31.38	-29.44	1,714
4	B/D	6/12/79	1136-1453	2	46.5 (S.D.=2.3)	639.2 (S.D.=83.6)	.00695	.00059	-32.57	-30.63	1,300
5	B/D	6/12/79	1944-2058	3			.00827	.00072	-31.82	-29.88	399
6	B/N	6/13/79	0024-0130	3	47.1 (S.D.=2.6)	[2/]	.00453	.00037	-34.43	-32-49	694
7	S/N	7/12/79	2310-0000	4	22.1 (S.D.=3.2)	87.2 (S.D.=33.1)	.00219	.00016	-37.59	-27.00	720
8	S/N	7/22/79	0051-0200	5	16.1 [3/] (S.D.=3.9)	33.5 (S.D.=29.9)	.00184	.00010	-38.34	-23.59	1,343

[1/] B = Aleutian Basin S = Shelf D = Day N = Night [2/] Individual weight measurements not taken.
[3/] Distribution was bimodal with about 60% of the fish with lengths of 12 to 16 cm.

Only juvenile fish (<30 cm) were captured during target strength data collection on the continental shelf (samples 7 and 8). As mentioned earlier, the target strength samples from the shelf were obtained only at night because single fish echoes were rarely detected during the day. Even at night, only selected portions of the data could be analyzed. Because the single target acceptance algorithm does not perform well in situations where there are many overlapping targets, only those portions of the data that appeared to be composed primarily of resolved single echoes were selected for analyses. This selection was based on a careful examination of echogram records. Sample 7 (22 cm mean length) had a mean value of -27.0 dB/kg; sample 8 (16 cm mean length) had an average value of -23.6 dB/kg.

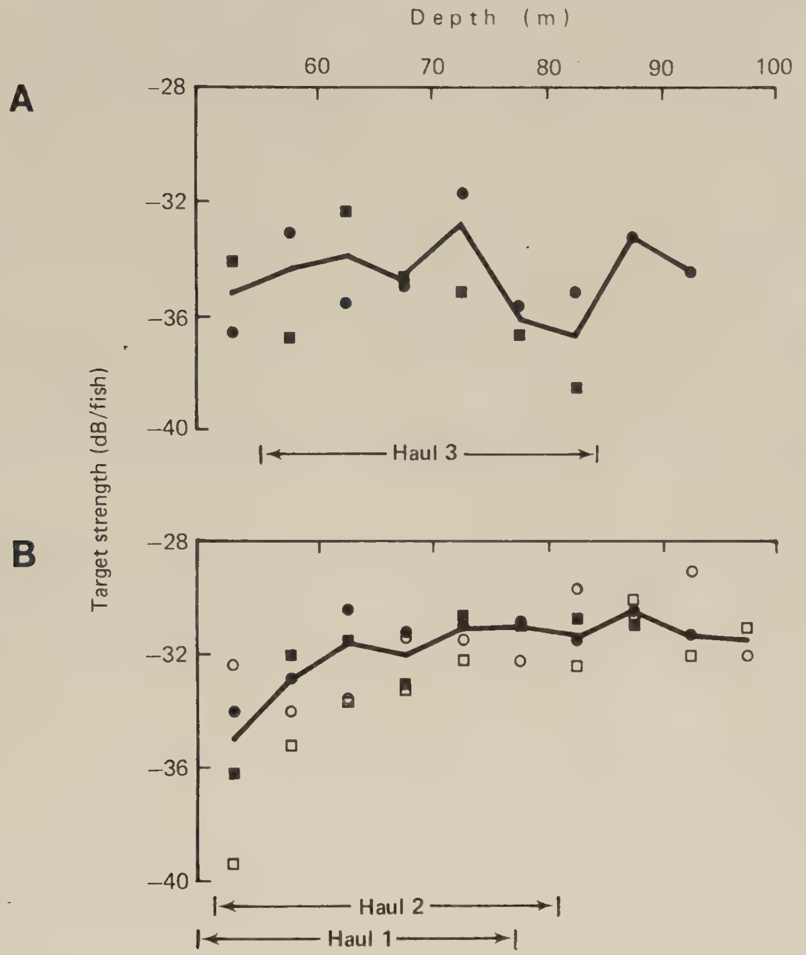

Fig. 2. Variation in pollock target strength with depth for the two nighttime samples (a) and the four daytime samples (B) in the Aleutian Basin. Each data point is the target strength of the mean scattering cross section estimate averaged over the 5 m depth interval centered at that point. The solid lines represent average target strength values. The portion of the water column sampled by each midwater haul made to identify echo sign is indicated.

For Aleutian Basin measurements, a noticeable change in target strength was observed with depth for the daytime samples (Fig. 2). The target strength of the mean scattering cross section ranged from a mean value of -35.1 dB/fish in the 50 to 55 m depth interval to -30.5 dB/fish in the 85 to 90 m depth interval. Most of the change occurred at depths less than 65 m, after which the target strength values remained fairly constant. The nighttime target strength values ranged from -32.7 to -36.2 dB/fish but showed no consistent trend with depth (Fig. 2).

3.3 Discussion

The average difference of 2.8 dB/kg between day and night target strength estimates calculated from the Aleutian Basin samples is significant, particularly for each integration scaling. The use of the nighttime measurements to scale daytime integration values, or vice versa, would result in an error by a factor of 1.9 in the population estimate. The cause of this difference is unknown but, assuming visual cues are important for orientation, it could be related to differences in tilt angle (from the horizontal) between the two periods. During darkness, a fish would have no frame of reference with which to orient itself to the horizontal, whereas during the day it could more easily maintain a horizontal aspect. Little information is available on diel differences in tilt angle distribution. An inability to orient in periods of darkness has been reported by Barham (1971) for deep sea smelt observed at a depth of 500 m and by Woodhead (1966) for herring near the surface at night. Although the distribution of tilt angles and how this distribution changes with the fish's diel behaviour is probably species specific, it seems reasonable that, for most species, the range of aspect angles will be greater at night than during the day. Because target strength drops off rapidly with aspect angle (Nakken and Olsen, 1977), the greater aspect angle range at night would result in a lower mean target strength value.

Both samples of juvenile fish observed on the continental shelf had large target strength per kilogram values. Craig (1973) calculated the dependence of target strength per kilogram on length for three species using target strength to length information and a length-weight relationship and obtained similar results.

The increase in target strength with depth observed in the daytime Aleutian Basin samples is probably due to a decrease in the average tilt angle from horizontal as depth increases. This could result from vessel avoidance involving vertical fish movements (downward and away from the vessel) as reported by Olsen (1981). Another possibility is that the fish n the shallower detphs exhibit difference behaviour (such as feeding) than the deeper individuals.

The results of the dual beam data analysis for pollack illustrate some of the possible effects of variation in behaviour on _in situ_ target strength estimates. They demonstrate the importance of treating target strength as a dynamic parameter which is functionally related to fish behaviour. In particular, they further point out the need to obtain more behaviour specific _in situ_ target strength estimates, especially for accurate scaling of echo integrator data.

4. SIMULATION OF DUAL BEAM TARGET STRENGTH MEASUREMENT METHOD

4.1 Simulation description

As indicated earlier, the simulation was designed to examine the effects of noise and fish density on error in the dual beam method. It included the formation of echo returns from each individual fish within the beam, their superimposition, the addition of noise at the transducer face, the filtering that occurs within the receiving system, sampling of the resultant waveform, and the acceptance of echoes as being from single fish on the basis of pulse length. System parameters were matched as closely as possible to those of the system used to collect the pollock target strength measurements described earlier in this paper. For the simulation, the carrier frequency was 7.5 kHz. This is substantially below the 38 kHz signal of the system being simulated. However, the envelope waveform, which is of primary interest, is slowly varying relative to either the 7.5 or 38 kHz carrier signal, and the effects of echo addition as a function of phase relationships between targets will be similar. Also, since the signal is narrow band limited, little echo envelope information is lost. The primary reason for using the 7.5 kHz carrier frequency was that it required a sampling rate of only 30 kHz to obtain quadrature samples of the waveform as opposed to the 156 kHz rate which would be required for the 38 kHz signal. Quadrature samples (four per cycle at the carrier frequency) are required to completely describe the modulated waveform. The simulation involved the following procedures:

1) Selection of a mean fish density, λ_o(no./m^3).

2) Zeroing of two 900 sample arrays ($X_n(i)$ and $X_w(i)$), representing quadrature samples of the narrow and wide beam receiving channels, respectively, at 0.025 m intevals (30 kHz sampling rate) for a depth range of 18.75 to 41.25 m.

3) Positioning of N targets in the acoustic beam, where N is a Poisson density variate with mean $\lambda_o V$, and $V = ((R_2^3 - R_1^3)/3)\Psi$ is the volume of the acoustic beam

between ranges R_1 and R_2 within solid angle Ψ. Each target was randomly positioned with respect to depth (R) and the off-axis angle (θ) to obtain a uniform spatial distribution of targets.

4) Calculation of narrow, $b_n(\theta)$, and wide, $b_w(\theta)$, beam directivity factors. For the simulation, R was constrained between 20 and 40 m and θ was less than 0.2 radians (11.46°), which included the main lobe of the transducer and the first side lobe.

5) Generation of a log normal cross section variate, σ. Assuming an ideal 40 $\log_{10}$ R+2αR time varied gain correction, narrow, $E_n(s)$, and wide, $E_w(s)$, beam voltages for the quadrature samples will then be:

$$E_n(s) = K\sigma^{\frac{1}{2}}\cos(\pi s/2+\phi)b_n^{\frac{1}{2}}(\theta), \quad \text{and}$$

$$E_w(s) = K\sigma^{\frac{1}{2}}\cos(\pi s/2+\phi)b_w^{\frac{1}{2}}(\theta)\ b_n^{\frac{1}{2}}(\theta)$$

where K is a system constant, s is the sample number within the target, and θ is a random phase angle. The width of the target was chosen to be 14 samples (0.35 m) to match those obtained using the system being simulated.

6) Summation of resulting modulated echo amplitudes into the appropriate quadrature sample locations corresponding to the depth generated in step 4, with the midpoint of the target located at R.

7) Generation of a variate from a Gaussian noise distribution with zero mean and the appropriate variance to obtain the required signal to noise ratio (SNR) 3/ for each of the 900 sample locations. The noise was summed with corresponding quadrature samples described above.

8) Filtering of the waveform using a digital filter designed to match the bandpass of the actual system.

9) Detection of the resultant waveform to obtain envelope detected signals, $D_n(i)$ and $D_w(i)$, for the narrow and wide channels, respectively:

$$D_n(i) = X_n^2(2i) + X_n^2(2i-1) \quad \text{and}$$

$$D_w(i) = X_w^2(2i) + X_w^2(2i-1)$$

Since two quadrature samples are required to generate one detected sample, these arrays contained 450 samples and simulated sampling of the detected signal at a 15 kHz sampling rate.

10) Acceptance of single targets on the basis of half amplitude pulse length.

11) Repetition of steps 2-10 until the desired number of accepted targets was obtained. Fig. 3 shows an example of the sampled waveform at various stages of the simulation. Only first order scattering was simulated, (i.e., multiple scattering and shadowing were not included).

Normalized bias (B) and normalized root mean square (RMS) error of mean scattering cross section estimates were calculated as:

$$B = (\hat{\bar{\sigma}} - \bar{\sigma})/\bar{\sigma} \quad \text{and}$$

$$\text{RMS error} = (B^2 + \text{Var}\ (\hat{\bar{\sigma}}))^{\frac{1}{2}}/\bar{\sigma}$$

3/ SNR = $\overline{TS}$ - RMS noise level (dB).

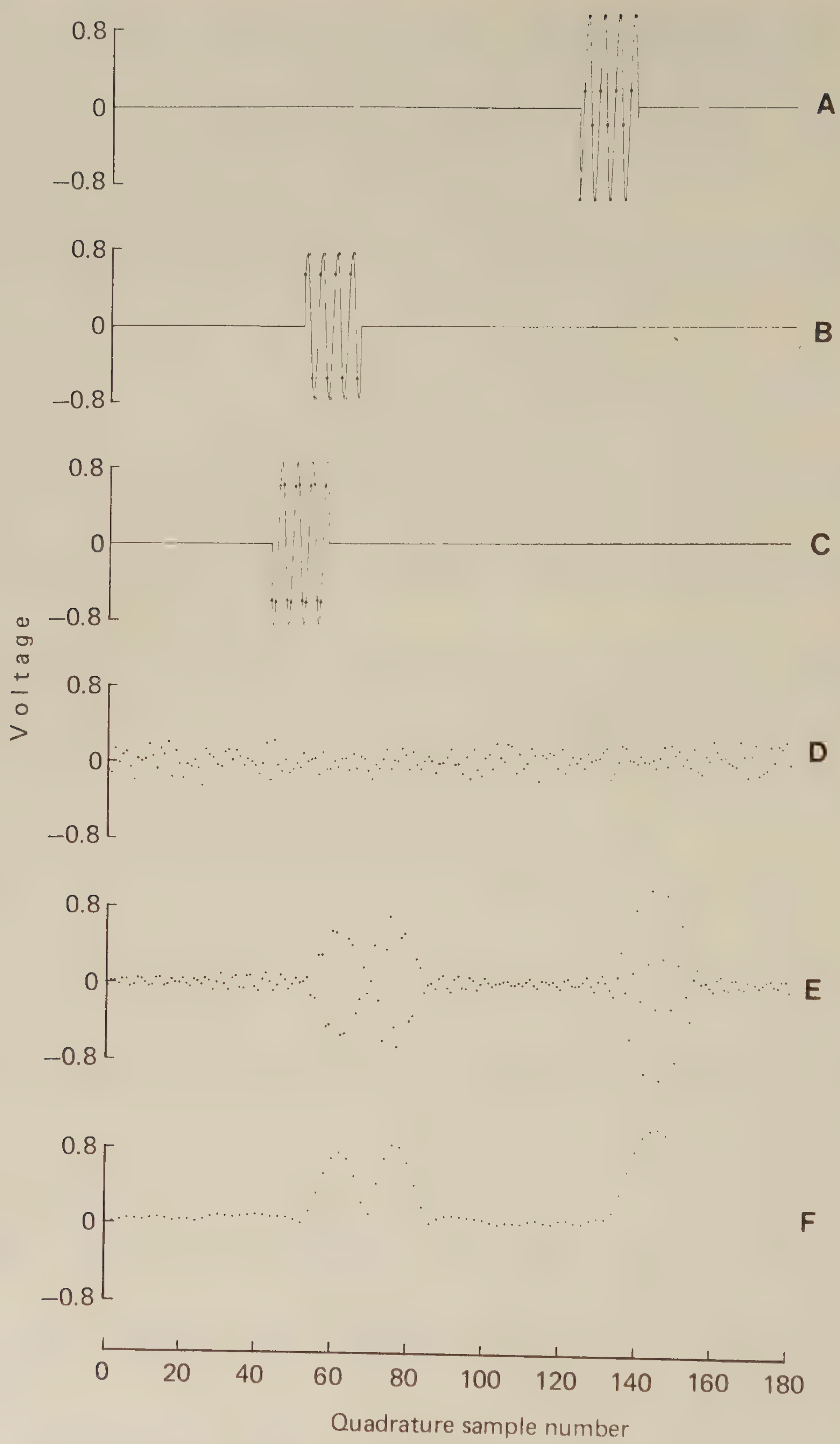

Fig. 3. Representation of the sampled waveforms at various stages of the simulation. A–C represented the waveforms of three targets (quadrature samples indicated by dots). D shows the samples of Gaussian noise. E represents the filtered sum of quadrature samples from the targets and of noise. F is the samples obtained by detecting the waveform in E.

Sixteen simulation runs were completed. Each run terminated when 6,000 targets had been accepted for analysis. Four runs were designed to examine the effects of noise on the dual beam method. These runs had target strength standard deviations (TSSD) of 2.5 and 5 dB, each with SNR values of 20 and 30 dB. These target strength and noise parameters were chosen as values likely to be encountered in the field. The targets were placed systematically at 2 m intervals within the depth region to ensure that no multiple targets could occur. To examine the effects of density on the dual beam method, 12 simulations using average density values of 2, 5, 10, 20, 40, and 80 targets within 0.2 radians of the acoustic axis at ranges of 20 to 40 m were used at each of two SNR values (20 and 30 dB) and with TSSD = 5 dB. As a reference, an average density of 80 targets within 0.2 radians of the acoustic axis corresponds to 11.53 targets within .091 radians ($b^2 = -20$ dB) and 5.78 targets within .054 radians ($b^2=-6$ dB).

4.2 Results

Analysis of the data from the four simulation runs in which no multiple targets occurred indicated that a beam pattern threshold (T_b) of -2 to -4 dB minimized the RMS error in dual beam target strength measurements in three of the four runs (Fig. 4). In the single case when the minimum RMS error did not occur in the -2 to -4 dB range (Fig. 4b, SNR=-30 dB, TSSD=5 dB), the RMS error at -3 dB was nearly as small as that for the minimum at -10 dB. This indicates that a beam pattern threshold of -3 dB would be an adequate choice for that case as well. Also included in Fig. 4 are plots of the bias for the four runs. For the sample sizes of 6,000 used for this study, the bias is the major contributor to RMS error. Ehrenberg (1978b) obtained similar results in an analytical simulation of the dual beam method which did not include target formation and summation or the effects of filtering and single target recognition.

The effect of density on error in the dual beam method is shown in Fig. 5. For both SNR values simulated, normalized RMS error was less than 0.1 for beam pattern thresholds from -3 to -6 dB and densities up to 20 targets within 0.2 radians of the acoustic axis between 20 and 40 m. This density corresponds to an average number of overlapping targets per ping (with both targets exceeding four times the noise threshold) of 0.07 and 0.34 for the 20 and 30 dB SNR simulations, respectively. In the high SNR situation, choice of beam pattern threshold is less critical than in the low SNR case. Although the simulations were completed in the 20-40 m depth range, the results apply to all depth ranges, i.e., a density of 80 targets within 0.2 radians of the acoustic axis in any 20 m depth interval will result in the same error if the SNR is the same.

The choice of pulse length acceptance window is critical in situations where multiple targets are likely to occur. The window (centered about the expected pulse length) cannot be set too narrow or many valid targets will be rejected; it cannot be set too wide or many noise spikes and multiple echoes may be accepted as valid targets. Fig. 6a shows the effect of pulse length acceptance window on RMS error of $\bar{\sigma}$ at $T_b = -3$ dB with a noise threshold equal to two times the RMS noise level; at pulse length acceptance windows greater than about 0.2 ms, error increases due to the acceptance of more noise spikes as valid targets. For a window of less than this value, a significant number of valid targets are rejected. For a larger noise threshold (T_n equals four times the RMS noise level), error is much higher in the 0.05 to 0.3 ms acceptance window range. This is due to the increased bias against small targets imposed by the higher noise threshold. Fig. 6b shows the effect of pulse length acceptance window on sample size. In the low noise threshold situation, reduction in the acceptance window from 0.6 to 0.25 ms results in the rejection of a small number of accepted echoes, primarily noise that has exceeded the threshold. As the window size is reduced below 0.25 ms, the number of accepted echoes decreases rapidly due to the rejection of more valid echoes. When the noise threshold is set at four times the noise level and the widest acceptance window (0.6 ms) is imposed, the sample size (2,420) is reduced about 25% below the sample size (3,214) using the lower noise threshold with the same acceptance window. The higher threshold rejects essentially all noise. However, it also causes a large percentage of the small echoes to be rejected, resulting in an increased bias against small targets.

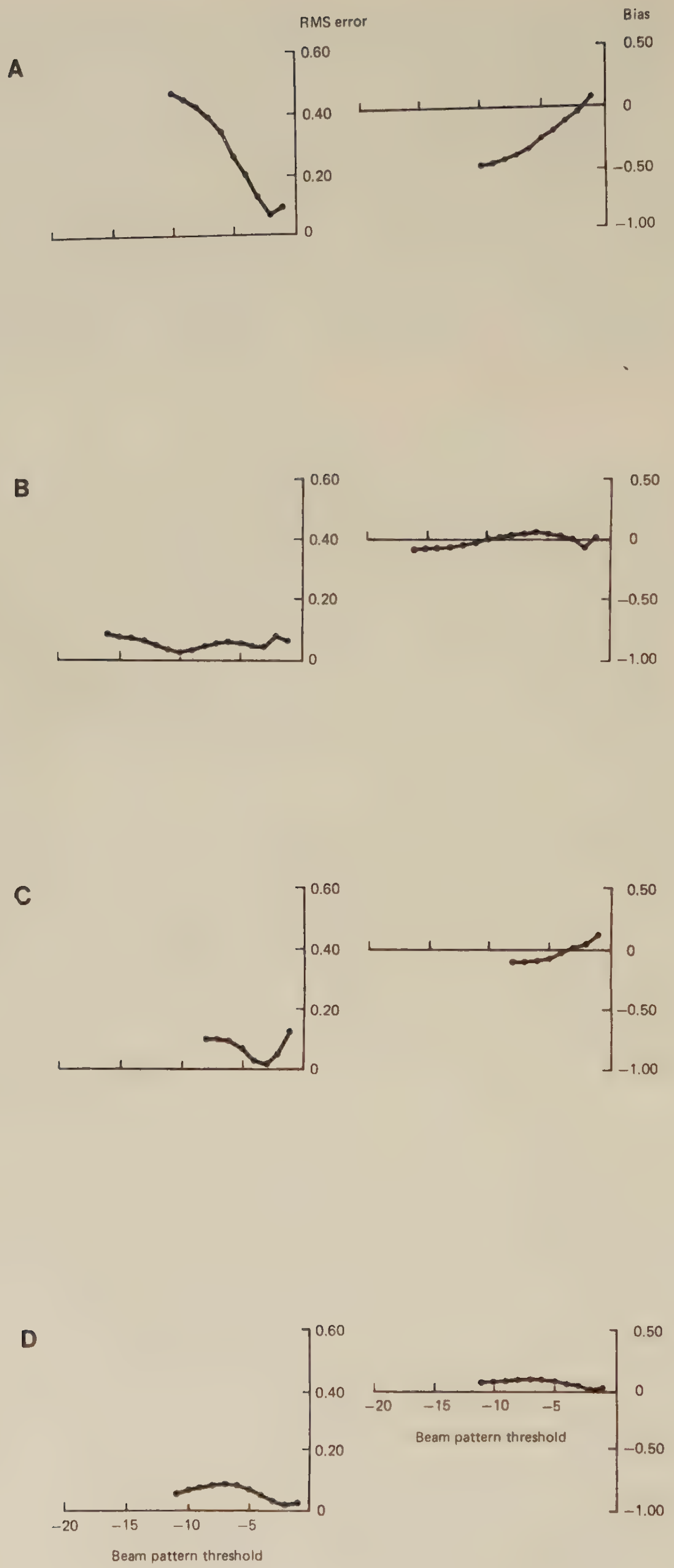

Fig. 4. Normalized RMS error and normalized bias in estimates of $\bar{\sigma}$ when nomultiple targets occur for (A) TSSD = 5 dB, SNR = 20 dB; (B) TSSD = 5 dB, SNR = 30 dB; (C) TSSD = 2.5 dB, SNR = 20 dB; and (B) TSSD = 2.5 dB, SNR = 30 dB.

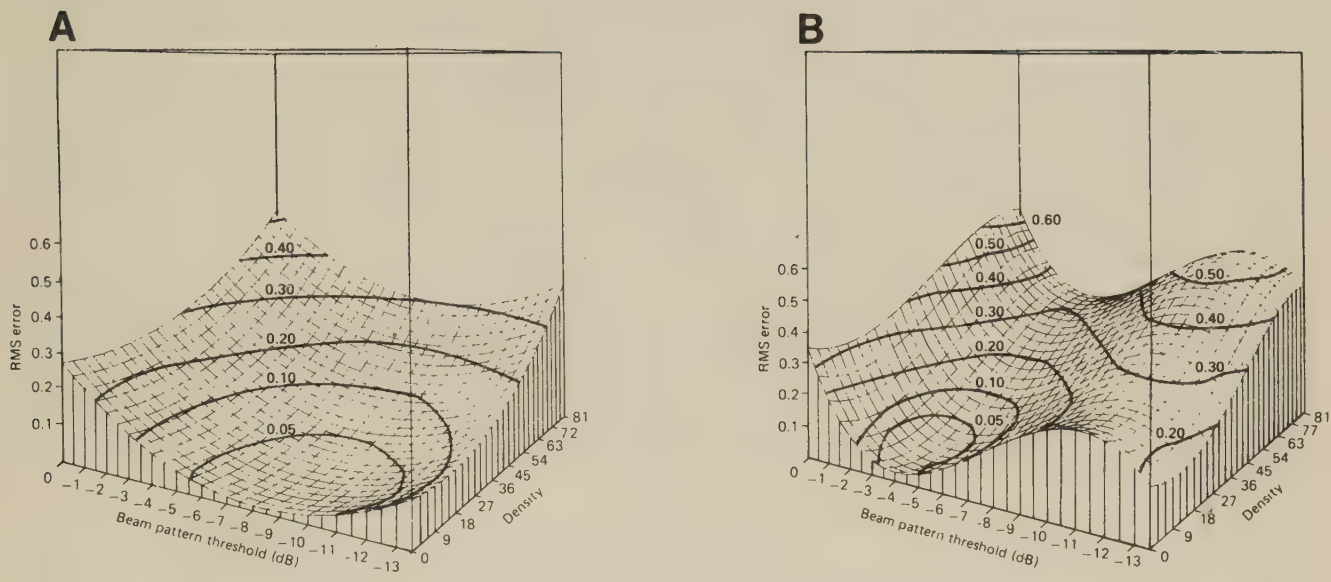

Fig. 5. Normalized RMS error in estimates of $\bar{\sigma}$ as a function of beam pattern threshold (T_b) and fish density (mean number within 0.2 radians of $\bar{\sigma}$ the acoustic axis between 20 and 40 m) for SNR = 30 dB (A) and 20 dB (B).

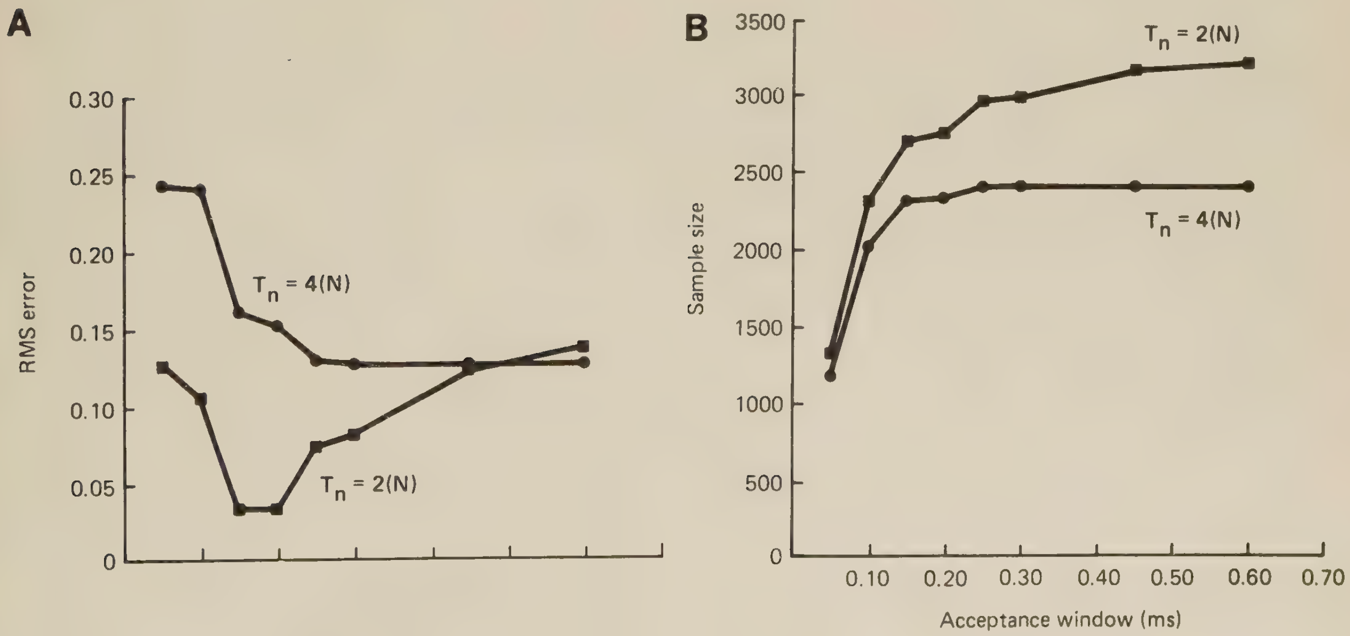

Fig. 6. Effect of pulse length acceptance window on the RMS error (A) of $\hat{\bar{\sigma}}$ and the number of single targets accepted (B) for noise threshold (T_n) two and four times larger than the RMS noise level. For this analysis, an SNR of 20 dB and a T_b threshold of -3 dB were used and no multiple targets were allowed to occur.

4.3 Discussion

In a field situation, the actual SNR is unknown. The simulation data reported here indicate that, for a large sample (6,000 targets), a reasonable beam pattern threshold to use is -3 dB. Even for the low SNR case, this choise of beam pattern threshold will provide normalized RMS errors less than 0.1 for densities as high as 30 targets within 0.2 radians of the acoustic axis between 20 and 40 m. For the system under study, a pulse length acceptance window of 0.2 ms around the mean pulse length minimizes error in estimates of $\bar{\sigma}$.

The simulation attempted to include most processes involved in the formation of echoes and the conditioning within the receiving system. For many situations, the assumption of a random distribution in the beam within a depth slice is not unreasonable. However, any tendency toward clumping will cause a higher number of multiple targets and larger errors for a given density. The assumptions of Gaussian distributed target strength and noise level may be reasonable for many survey situations.

Since the cause of the increase in error as density increases is the occurrence of multiple targets, the data presented on error in the target strength measurements can be used as a guide for other in situ techniques. For average densities up to about six fish in the volume bounded by a two-way directivity (b^2) of -20 dB in a 20 m depth slice, the error due to the occurrence of multiple targets will be minimal for TSSD's of about 5 dB and SNR's of 20 and 30 dB. The error should be independent of transducer beam width except as it affects the SNR and sample volume.

FIRST LOOK AT HERRING DISTRIBUTIONS WITH A BOTTOM REFERENCING UNDERWATER TOWED INSTRUMENTATION VEHICLE "BRUTIV"

by

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ABSTRACT

An underwater towed instrumentation vehicle was used to photograph spawning and prespawning herring during day and night. In daytime, the herring seem to swim in schools more or less horizontally, with all the fish in each school going in the same direction. At night, there appears to be no organized pattern of swimming. Individual fish in the aggregations face in almost every direction and are tilted from horizontal to head up or head down.

RESUME

La densité des détections acoustiques du posson dépend de plusieurs facteurs, dont les principaux sont la taille des poissons et leur aspect dans le faisceau acoustique. Nous décrivons dans l'article qui suit la distribution des angles d'inclinaison de harengs en voie de ponte ou avant la ponte. Nous avons utilisé à cette fin des photographies prises par caméra montée sur véhicule sous-marin toué. Les photos prises le jour indiquent que les harengs nagent plus ou moins horizontalement, tous les individus d'un banc erant orientés dans la même direction. Celles prises la nuit ne montrent aucun ordre, les harengs nageant dans presque toutes les directions, leur position variant d'horizontale à inclinée, la tête vers le haut ou vers le bas.

1. INTRODUCTION

The need to study herring behaviour at sea arises from the need to make stock abundance estimates. Such estimates are difficult to make on pelagic species by the traditional methods but acoustic methods show promise.

The accuracy of acoustic abundance estimates, however, is directly proportional to the accuracy with which the acoustic target strength of the surveyed fish can be estimated. Target strength is a function of many factors, foremost being the size of the fish and the aspect of the fish in the sound beam. The importance of size has been recognized and size is easily and routinely measured in acoustic surveys. The importance of aspect, although there is plenty of evidence for it (Midttun and Hoff, 1962; Nakken and Olsen, 1977; Buerkle, 1979), has been largely ignored and needs to be emphasized. In cod, for example, the target strength of fish tilted 45° head down, is 12 dB lower than the "dorsal aspect" target strength of horizontal fish (Buerkle, 1979). If the dorsal aspect target strength were applied in an abundance estimate of such fish, the estimated abundance would be only about 6% of what it should be. If, or how often, such behaviour occurs has not been explored systematically. There is evidence that fish at sea display a wide range of aspects (Barham, 1970; Kiselev, 1968; Lagunov, 1955; Ryzhenko _et al_. 1961) but this is mostly anecdotal rather than quantitative. Two attempts to measure tilt angle distributions of fish at sea have been made (Olsen, 1971; Carscadden and Miller, 1980). Both lowered cameras into fish concentrations from a stationary vessel and the usual doubts about the influence of the camera on fish behaviour arise. Recent observations (Olsen, 1979) show that herring change behaviour in response to a vessel passing overhead. The change starts about 50 m ahead of the bow and persists for about 100-200 m behind the vessel. If this is a general

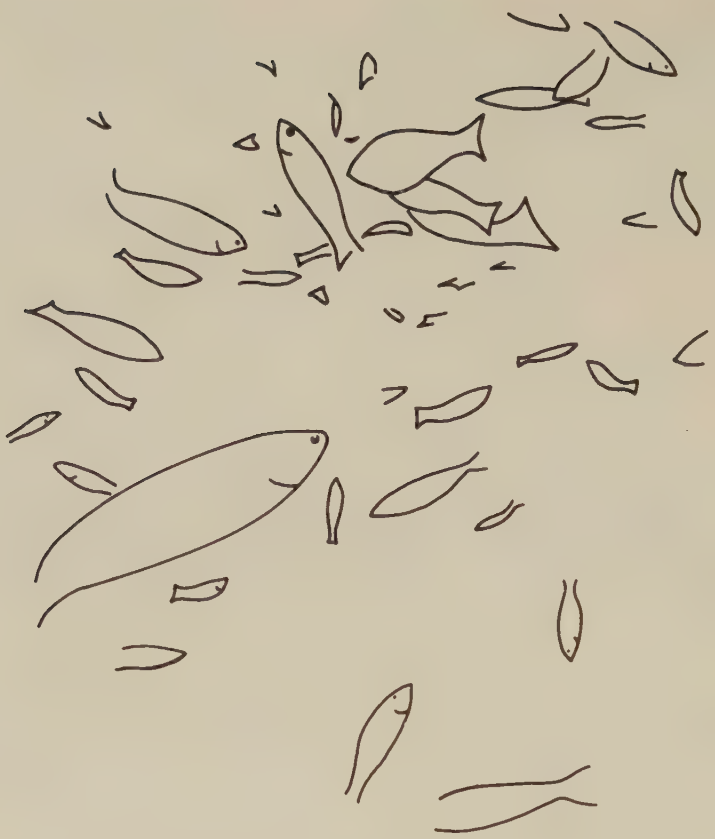

Fig. 1. Tracings of the outlines of fish and visible portions of fish from a nighttime photograph.

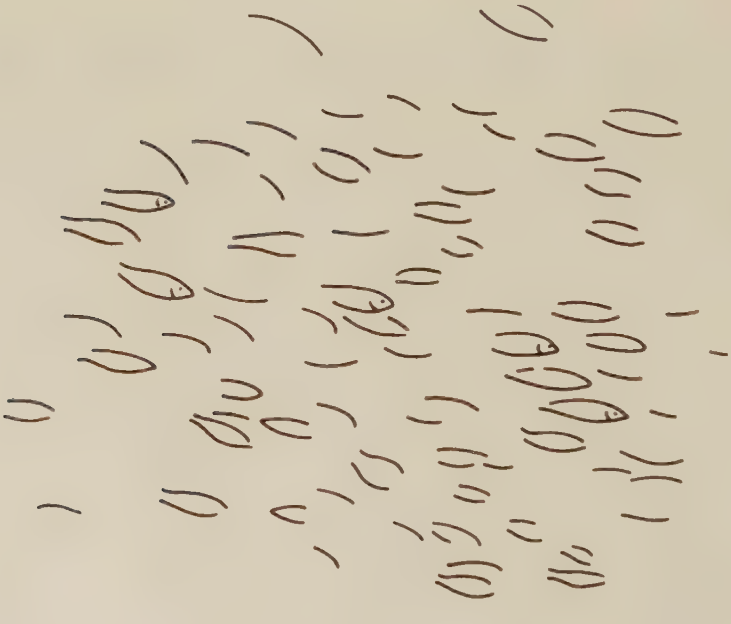

Fig. 2. Tracings of outlines of fish and visible portions of fish from a daytime photograph.

response, then the tilt angle distribution of interest in determining target strengths for acoustic surveys is the distribution under the moving survey vessel, and cameras lowered from stopped survey vessels do not observe this distribution. A towed camera, on the other hand, can observe the fish, not directly under the moving vessel, but a short distance behind, and has the potential for observing the required tilt angle distribution.

2. METHODS

The Bottom Referencing Underwater Towed Instrumentation Vessel BRUTIV (Foulkes, 1980) was developed at St. Andrews, primarily to carry cameras and television to study behaviour and distribution of marine animals from moving vessels. It is a glider with servo-controlled wings that can fly at constant altitudes above the sea bed or at constant depths below the sea surface. Flight mode and parameters are controlled from the towing vessel. Flight data such as altitude, depth, pitch, roll and the television can be monitored from the surface vessel.

BRUTIV was used to photograph spawning and prespawning herring concentrations in St. Marys Bay in August and September 1980. The fish were found in shallow water (20 m) in dense concentrations and were being fished commercially by seiners and gillnetters. BRUTIV was towed by the 19-m research vessel J.L. HART on about 60 m of cable. The photographs were made with two 35-mm Edgerton cameras and strobe lights. The starboard camera was mounted to view 90° to starboard at the front of the vehicle; its light was mounted at the back of the vehicle (2.5 m away from the camera) pointing about 45° ahead. The port camera was mounted at the rear of the vehicle to view 45° ahead on the port side; its light was mounted to point 90° to port at the front of the vehicle. The starboard camera was used during day and night; the port camera was used at night only.

3. RESULTS AND DISCUSSION

3.1 Results

Most of the time at sea was spent hunting for fish and maneuvering BRUTIV through fish concentrations. Because of the small size of the concentrations (often less than 100 m in diameter) and the presence of the commercial fleet, this was a frustrating process involving many attempts and precise navigation.

Approximately 4500 night and 1100 day photographs were taken; 674 of the night and 99 of the day photographs showed fish. Tracings of the outlines of fish and of visible portions of fish are shown for a night photograph in Fig. 1 and for a day photograph in Fig. 2. Tracings rather than actual photographs are presented because contrast in the color slides is low and they do not enlarge and reproduce well in black and white. Also, many of the fish were poorly or only partially illuminated, and some show in silhouette against a lighter background.

The orientation of primary interest for target strength determination is the pitch angle of the fish. Pitch angles of fish in monocular (i.e. non-stereo) photographs can be determined only for fish that are parallel to the photographic plane. Stereo-photography would allow pitch angle measurements of fish at other orientations and is planned for future work.

Only a small fraction of all the fish photographed is parallel to the photographic plane. Pitch angle measurements were made on the fish that appeared parallel to the photographic plane and only on photographs that showed at least five such fish. Nighttime pitch angles were measured on 229 fish in 35 photographs from the starboard camera and on 241 fish in 35 photographs from the port camera. Daytime pitch angles were measured on 158 fish in 14 photographs from the starboard camera. Figures 1 and 2 show the difference between day and night behaviour.

Typical results of pitch angle measurements are shown in Fig. 3. It shows pitch angles on five of the night photographs from the starboard camera and the pitch angles

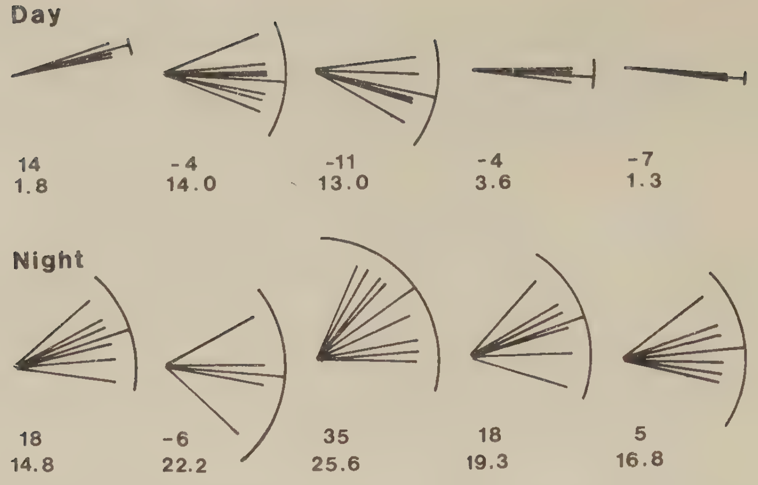

Fig. 3. Pitch angles of fish on five night and five day photographs from the starboard camera with mean (upper number) and standard deviation (lower number). Short lines are individual fish angles; the long line and the arc represent the mean ± standard deviations.

Table 1. Frequency distribution of herring pitch angles during day and night in 5° groups. (+ = head up, - = head down)

Pitch angle	Night frequency	Day frequency
+75 to +79	4	
+70 +74		
+65 +69	5	
+60 +64	4	
+55 +59	2	
+50 +54	5	
+45 +49	9	
+40 +44	14	
+35 +39	21	
+30 +34	40	
+25 +29	43	
+20 +24	50	2
+15 +19	33	4
+10 +14	35	15
+ 5 + 9	32	15
0 + 4	34	23
- 1 - 5	34	25
- 6 -10	30	29
-11 -15	17	31
-16 -20	19	11
-21 -25	10	2
-26 -30	11	1
-31 -35	7	
-36 -40	4	
-41 -45	2	
-46 -50	3	
-76 -80	1	
-91 -95	1	
Total	470	158
Mean pitch angle	12.0	-3.4
Standard deviation	23.5	10.3

on five of the day photographs. Each line in the sets of radiating lines is the pitch angle of one fish drawn facing right. All the angles are drawn facing right because orientation in the horizontal plane does not affect target strengths of fish in the center of the acoustic beam and the spread of the measurements about the mean is better illustrated when all angles are in the same direction. Each set of lines represents measurements on one photograph. The long line joined to the arc in each set is the mean of the measurements; the arc extends two standard deviations on each side of the mean. A summary of all measurements in 5° groups together with the mean day and night pitch angles and their standard deviation is shown in Table 1.

All fish in each of the 99 day photographs swim more or less horizontally and more or less parallel to the two path (pitch angle measurements could be made on only 14 of the 99 photographs because most fish were too far away and poorly illuminated to make measurements). As in Fig. 2, all fish in every one of the 99 photographs swim more or less in the same direction. In 9 of the 14 photographs (64%) all the fish faced left - they swam with the tow; in the other five photographs (36%) all the fish faced right - they swam against the direction of the tow. The fish that can be observed from BRUTIV in daytime then seem to swim in schools, more or less horizontally and parallel to the tow path, either with or against the direction of the tow and keep well away from BRUTIV.

Nighttime photographs do not show an organized pattern of orientation. Individual fish point in almost every direction. Although there are exceptions, Fig. 1 is typical. On the photographs from the starboard camera about 80% of the fish for which pitch was measured faced towards the left and therefore swam in the same direction as the tow. The other 20% faced towards the right and swam against the tow. On the photographs from the port camera about 60% of the measured fish faced towards the left and therefore swam away from the tow path at about 45° towards the stern. The other 40% faced towards the right and swam at 45° towards the tow path. Many of the fish at night seem to swim more or less with or away from the tow but proper evaluation of swimming direction in the horizontal plane requires stereo-photography or a vertically viewing camera.

3.2 Discussion

Although the cameras are equipped with data chambers that are meant to record time of day, exposure number, altitude, depth, pitch, roll and speed of the vehicle, none of this information was recorded because of electronic malfunctions. The attitude of BRUTIV for each photograph is therefore not known. BRUTIV attitude does vary from the horizontal in normal flight; the degree of pitch and roll at any one instant is probably only a few degrees but depends on operating conditions such as speed, scope ratio, tidal currents, and weather. The pitch angles presented should therefore be accepted with reservations. It does seem that the mean day pitch angle is about 3° head down, and the mean night pitch angle is about 12° head up.

The spread in pitch angles on any one photograph is not affected by BRUTIV attitude. There is a striking difference between day and night spread. The daytime standard deviation is 10.3°. The nighttime standard deviation is 23.5°. This difference is thought to quantify a real difference in day and night behaviour.

The question of whether these behaviours are "normal" for herring under a moving survey vessel remains. The daytime schooling observed may well be influenced by visual contact with BRUTIV. The nighttime disorganization is more difficult to visualize as a result of the presence of BRUTIV. The influence of BRUTIV at night can be further explored by using slower flash rates and/or faster towing speeds so that concecutive flashes are out of visual range of each other and the herring would be unaware of the approach. Noise generated by BRUTIV does not seem to be a possible stimulus for fish (Buerkle, in prep.).

If the observed behaviour difference is real, it would result in a difference in day and night target strengths. Analysis of measurements of herring target strengths in relation to aspect in the sound beam is not complete (Buerkle, in prep.) but results indicate that the target strength of the observed nighttime distribution may be about

6 dB lower than that of the daytime distribution. Applying the wrong target strength in acoustic abundance estimates would result in estimates that are one quarter or four times what they should be.

ACKNOWLEDGMENTS

This work is made possible by the availability of BRUTIV for which T.J. Foulkes deserved credit and by help and support from Sam Polar, John Trynor, and Captain Guptill and his crew.

OBSERVED FISH REACTIONS TO A SURVEYING VESSEL WITH SPECIAL REFERENCE TO HERRING, COD, CAPELIN AND POLAR COD

by

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ABSTRACT

The paper presents the results from a series of observations on fish reactions to an approaching vessel. The observations have been made under varying conditions. Seasonal variations, species and size differences, density and depth distributions of fish have been studied using three different research vessels. The techniques used in the experiments included both acoustic methods and optic methods. There is a typical avoidance reaction pattern which becomes reduced with increasing swimming depth of the fish and with decreasing speed of the vessel. In addition, a local density reduction beneath the vessel occurs occasionally. The reaction patterns described are shown to be typically "directional" with the fish moving away from the approaching vessel with an increasing downward tilt.

RESUME

Ce document présente les résultats d'une série d'observations concernant les réactions du poisson à l'approche d'un bateau. Les observations ont été effectuées dans diverses conditions. Les effets des variations saisonnières, des différences d'espèces et de taille, de la distribution en profondeur et de la densité du poisson ont été étudiées en utilisant trois bateaux de recherche différents. Des méthodes acoustiques et optiques sont inclues dans les techniques employées. Des observations ont montré des exemples typiques de réactions d'évitement qui diminuent avec l'augmentation de la profondeur des poissons et de la diminution de la vitesse du bateau. Les réactions décrites ont été clairement "directionnelles", le poisson fuyant à l'approche du bateau avec un augmentation de l'angle d'inclinaison.

1. INTRODUCTION

Fish in nature show a great number of behavioural reactions adapted to their various life strategies and may also show particular typical behavioural patterns adapted to certain biological situations. Previous experiments have shown that herring and related species display avoidance reactions when exposed suddenly to low frequency noise stimuli, for example noise from fishing vessels (Hering, 1968; Olsen, 1969 and 1971; Urquhart and Hawkins, 1975). A typical reaction is a turning away from the vessel and the beginning of a descent.

Vessels unavoidably generate noise stimuli in the water, and these can be detected by fish at distances of several hundred meters. When a vessel is passing over concentrations of fish important questions to be answered include; what effect may such stimuli have on behaviour of fish in the vicinity of the vessel, and secondly, if we record these fish by echo sounders and if the behaviour is influenced; what impact could be expected on received fish echoes? Obviously, avoidance behaviour resulting in fish being scared out of the region beneath a surveying vessel will affect any estimation of fish abundance.

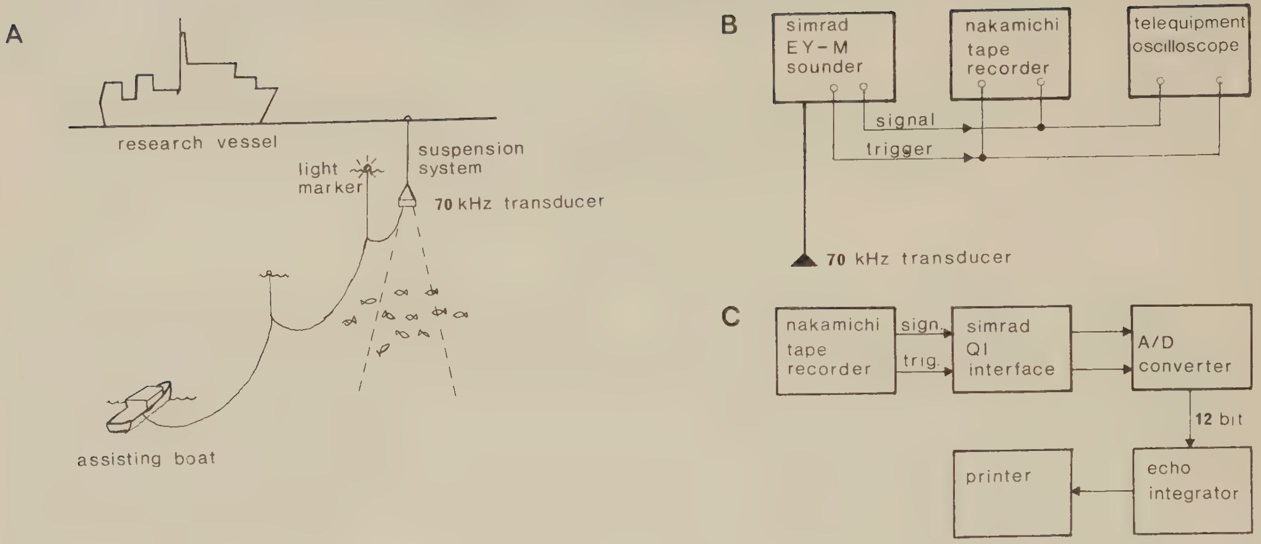

Fig. 1. The use of a submerged echo sounder transducer in studies of fish behaviour during passage of a surveying vessel.
A: Sketch of equipment in the field.
B: Block diagram of recording instrumentation.
C: Block diagram of play back and analyzing instrumentation.

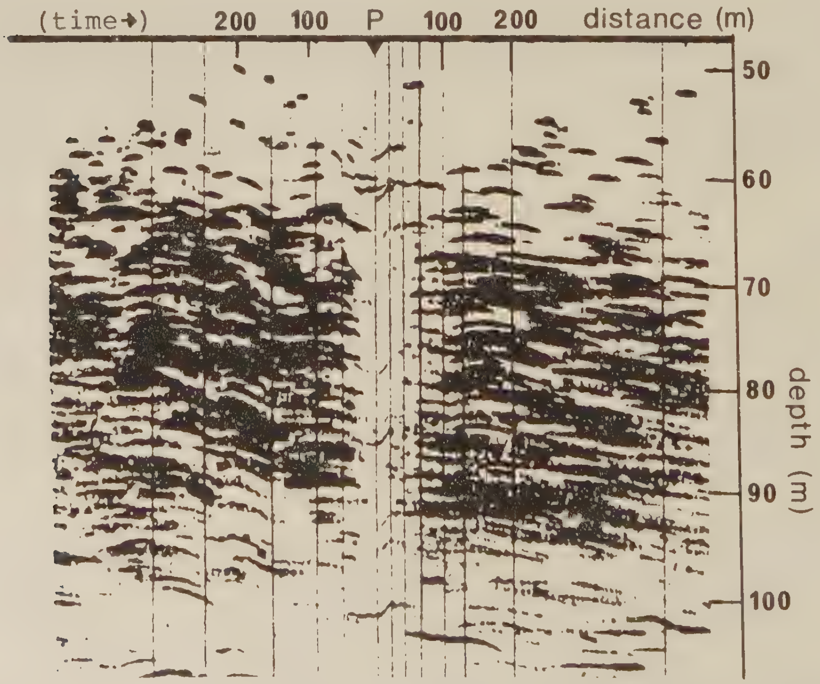

Fig. 2. Echo recording of herring, $\bar{l}$ = 10 cm at night obtained using the submerged echo sounder transducer of 45 m depth (R/V "Johan Hjort" running at 15 knots). (P) = vessel passage.

Echo sounders have been used for "fish-finding" for about 50 years, and, whilst there is little doubt as to the value of echo sounders in a qualitative sense, there is surprisingly little evidence demonstrating the reliability of the quantitative estimates of fish abundance using echo-location techniques. One fundamental problem in obtaining such information is that, when on board a surveying vessel, there are few possibilities for the collection of objective information about the situation before the vessel entered the area. Observations made by fishermen suggest that a vessel running at full speed above a fish school will very often have the effect of making the school descend and/or to avoid the vessel.

In reports presented by Olsen (1979, 1980 and 1981) a number of experiments were described aimed at elucidating the effects of variations in fish behaviour on hydroacoustic fish abundance estimation. This work has been continued and, in the present report, observations of the behavioural reactions of four different fish species subjected to disturbance by approaching vessels are presented.

2. OBSERVATION TECHNIQUES

Most of the methods used have already been described in earlier reports (Olsen, 1979 and 1980). A standard method, in all investigations, has been the use of a stationary, submerged echo sounder transducer positioned so that an approaching vessel passes directly over it. During the passage the change in the echo recording of the fish concentrated beneath the transducer could be obtained (Fig. 1). All echo signals were tape recorded and have later been integrated and analyzed for details of the behaviour patterns. Factors investigated include timing of events, variations in the reaction distance and depth distributions of reactions.

By use of underwater photography and television, a number of photographs and video tape recordings have been obtained showing the behaviour of fish within schools. By attaching a separate echo sounder transducer on to the camera housing, simultaneous pictures and recordings of echo signals could be obtained for given groups of fish. By controlling the orientation of the camera this method has given substantial information both about fish density and spatial orientation during the development of an avoidance reaction. In order to reduce disturbances in the schools caused by the presence of the camera, most of the photographs were taken in the dark.

UTV-observations were limited to light conditions where use of artificial light could be avoided. One technique used was to submerge the camera into the deepest part of a fish school and then orientate the camera towards the water surface. Under the best conditions it was possible to make simultaneous observations of the behaviour pattern of a fish school and the passage of the hull of the ship at the surface, from 40 m depth.

Two methods have been used on board the surveying vessel, in attempts to obtain improved information of the behaviour of fish during the echo recording. One method has been to produce greatly expanded signal fish echo traces by fast external triggering of the echo sounder and then displaying the echo received on a 50 cm graphic recorder. There are, however, certain limitations in the analysis of such echo traces. Recordings must be made on groups of fish which are sufficiently dispersed to allow isolation of echo traces from given individuals and of essential importance is exact knowledge of the tilt of the hullmounted transducer (Olsen, 1981).

The second method was to measure doppler shifts in the fish echo signals. The technique uses modified conventional sonars with the acoustic beam directed either downward, or at a fixed tilt angle when passing over concentrations of fish. The echo signals received were either frequency analyzed directly or recorded on tape for later computations. When analyzed, the frequency of the bottom echo signal is used as a reference and each estimation of doppler shift is based on an average value of 50 successive transmissions.

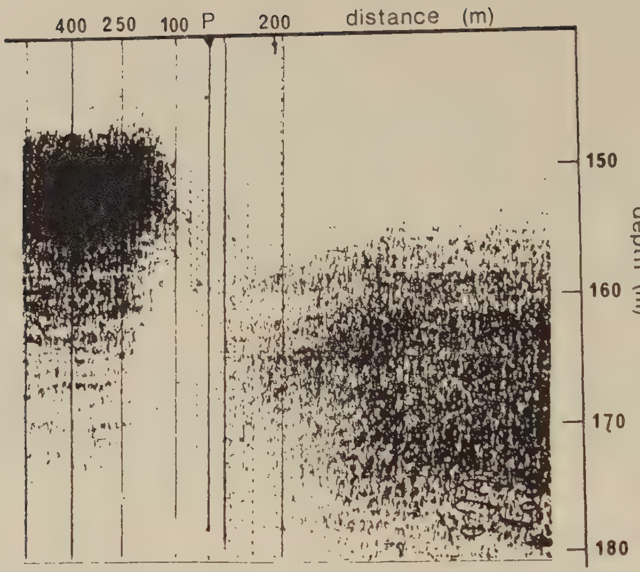

Fig. 3. Echo recording of polar cod, $\bar{l}$ = 11 cm at night obtained using the submerged echo sounder transducer at 40 m depth (R/V "G.O. Sars" running at 12 knots). (P) = vessel passage.

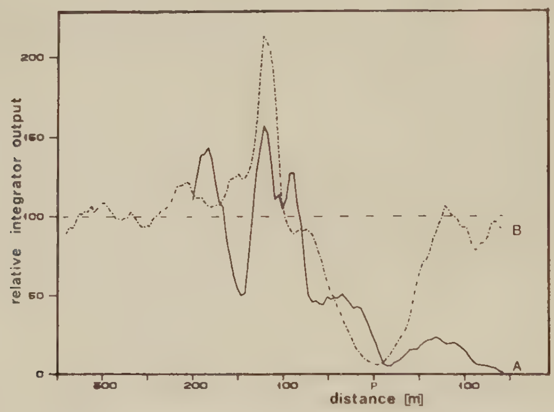

Fig. 4. Relative echo integrator output (running mean per transmission) computed from echo recordings obtained using the submerged transducer. A: herring, $\bar{l}$ = 22 cm at 25-50 m depth at night during vessel passage 10 knots) and B: herring, $\bar{l}$ = 10 cm, at 61-110 m depth at night (R/V "Johan Hjort", 10 knots).

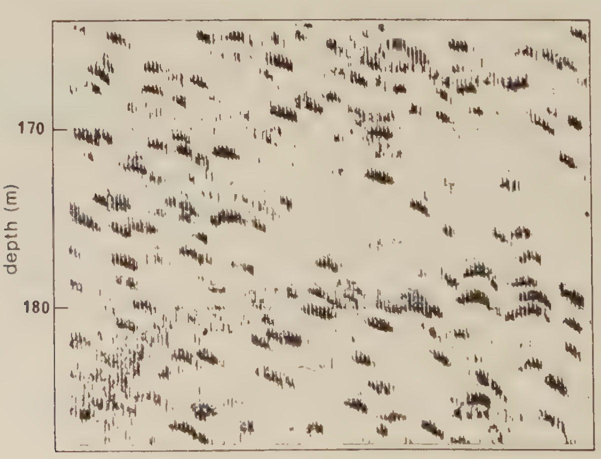

Fig. 5. Expanded scale echo recording of dispersed capelin, $\bar{l}$ = 14 cm, obtained from the ship mounted echo sounder (SIMRAD EK-120) in combination with a 50 cm graphic recorder (EPC 3200) (R/V "G.O. Sars", 8 knots).

3. BEHAVIOUR OBSERVATIONS

Fig. 2 shows a typical echo recording of small herring (l≅10cm) obtained by the stationary echo sounder submerged at 45 m depth, during the passage of R/V "Johan Hjort" (600 tons) at 10 knots (Olsen, 1980). When the vessel approached, the echo signals become significantly reduced, but return to the original level after a short interval. There also appears some tendency for the fish to descent.

Similar recordings have been obtained in a number of experiments when undertaking echo surveys in areas with concentrations of adult herring (Olsen, 1979 and 1980) and, more recently, when investigating in areas where other species as capelin, cod and polar cod are found.

The most dramatic changes in the echo recordings are usually seen when fish are aggregated close to the surface. When the fish are at greater depth, changes are less dramatic, but significant reductions have been recorded even at depth below 150 m (Fig. 3).

Information obtained by photographing and television have confirmed that the changes in the echo signals are related to changes in the behaviour of the fish. In a series of 6 runs crossing in different directions above a dense shoal of adult pre-spawning herring, all records showed fish moving away from the vessel (Olsen, 1981). Fish were at depths of 20-40 m and photographs were taken at night at distances 25-40 m in front of the approaching vessel. Comparison with estimates of fish density from pictures taken within fish schools in an undisturbed situation (photographs taken a few minutes before arrival of the vessel), indicated that significant reductions in fish density most commonly had occurred at the moment of vessel passage.

Video recordings obtained within the herring schools at the same depth in the same area at day time, showed that when the vessel was about 75-100 m away from the school a disturbance in the behaviour occurred. Fish turned away from the vessel. When the vessel approached closer, swimming became faster, the fishes became more equally orientated and they began to descend. When the vessel was directly above the school, swimming was very fast, steeply descending and with a characteristic pattern of "radiation" out of the vessel path. The schooling pattern was disrupted and the fish's reaction approach "panic fleeing". During this behaviour sequence, fish density, which so far had seemed relatively unaffected, very soon became drastically reduced.

A comparison between day and night observations did not indicate any great difference in reaction pattern. The visual conditions in the water during the daytime experiments were excellent (35-40 m visual range). There may, however, be a somewhat more pronounced density reduction beneath the vessel during daytime.

Fig. 4 shows two sequences of integrated echo intensity of recordings made by the submerged transducer, during two runs above concentrations of small and medium sized herring at different depths. In both runs a dramatic reduction in the integrator output is observed when the vessel passes, with the greatest reduction occurring when fish are at shallow depth.

In Fig. 5 is shown a recording of expanded single fish echo traces obtained when surveying in an area with scattered concentrations of capelin at 150-200 m depth. The recording demonstrates a significant downward "tilt" of the majority of the echo traces which indicates that a distinct downward migration of the fish is taking place. Such a downward migration may, however, take place even if the total acoustic back scattering is less significantly influenced (Fig. 6).

Fig. 7 shows typical echo integrated output obtained from recordings of the four different species of fish so far investigated. The herring recording was obtained from small, hibernating fish at 50-110 m depth when R/V "Johan Hjort" was running at 10 knots. The cod recording is of spawning cod in Lofoten with R/V "Johan Ruud" (300 tons) running at 10 knots. The capelin and the polar cod recordings were obtained during the feeding season in the Barents Sea when R/V "G.O. Sars" (1800 tons) was running at 12 knots. Despite the different recording conditions, all species showed

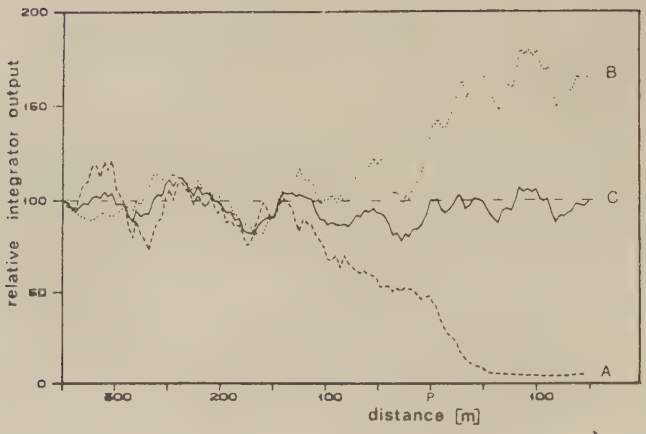

Fig. 6. Relative echo integrator output (running mean per transmission), computed from echo recordings obtained using the submerged transducer. A: Capelin, $\bar{l}$ = 14 cm, at 112-132 m depth at night during vessel passage (P), (R/V "G.O. Sars", 12 knots). B: Capelin, $\bar{l}$ = 14 cm, at 132-172 m depth in the same run. C: Sum of A and B, (analog to fig. 7/B.)

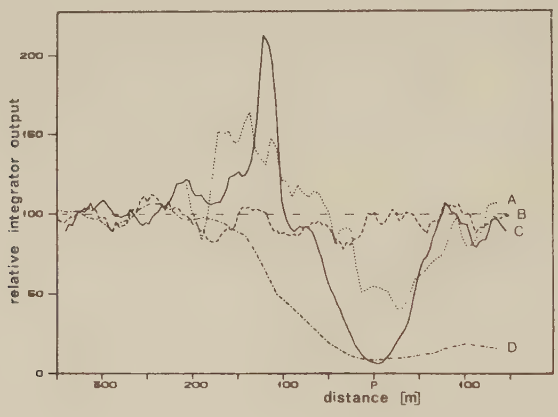

Fig. 7. Relative echo integrator output (running mean per transmission), computed from echo recordings obtained using the submerged transducer.
A: Cod $\bar{l}$ = 70 cm, at 70-130 m depth (R/V "Johan Ruud", 10 knt)
B: Capelin $\bar{l}$ = 10 cm, at 112-172 m depth (R/V "G.O. Sars", 12knt)
C: Herring, $\bar{l}$ = 10 cm, at 60-110 m depth (R/V "Johan Hjort", 10 knt)
D: Polar Cod, $\bar{l}$ = 11 cm, at 110-220 m depth, (R/V "G.O. Sars, 12knt)

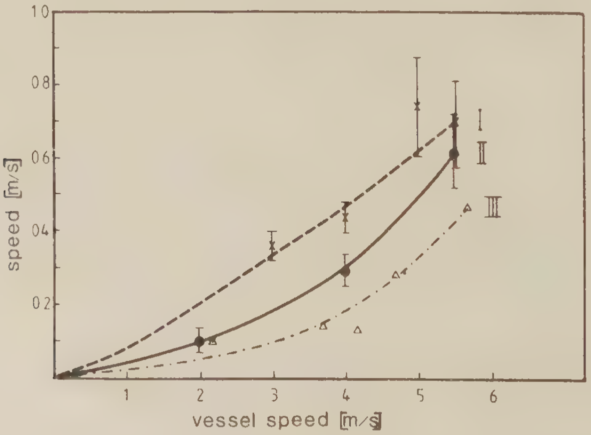

Fig. 8. Estimated descend speed obtained by doppler shift measurements of I: Herring at 40 m depth, II: Herring at 50 m depth, and III: Cod, at 100 m depth, as function of vessel speed (R/V "Johan Ruud").

considerable changes in behaviour when the vessel approached. Most pronounced seems the reaction shown by the polar cod, which appears to react when the vessel is more than 150 m away. At an almost similar distance the records in the herring and cod experiments start to show a transient increase before the decline typically observed during the passage of the vessel. This typical increase in integrator output before the vessel passes is assumed to be related to a changed spatial orientation of the fish.

After the passage of the vessel the behaviour of the fish, i.e. the spatial orientation, apparently soon return to that seen before the arrival of the vessel. The echo integrator output obtained at a time when the descending reaction is indicated to have ceased (50-75 m after passage), may be treated as an indication of to what extent a true reduction in fish density also has occurred. From diagrams as shown in Fig. 4 and 6, reduction in density at the moment of vessel passage of 70-80% is indicated in the shallow herring runs, in the shallow capelin run of 40-50%, and in the polar cod run even up to 90%. In other "deep fish" runs the density reduction appears to be insignificant.

Fig. 8 shows estimates of "descending speeds" based on dopplershift measurements obtained in two experiments conducted in herring and one on cod when the speed of the vessel was altered. The depth of the fish was about 40 m and about 50 m in the herring experiments and about 100 m in the cod experiment. The results indicate that the depth of the fish is of importance in determining the magnitude of the descend as well as the speed of the vessel. When assuming the fish to swim at cruising speed for both these groups of fish (of the order of 3 knots, Blaxter, 1969) the mean downward tilt of the schools of herring, when the vessel was at its maximum speed, may have been about $25-30^{\circ}$ and that of the cod about $15-20^{\circ}$.

The magnitude of the observed behaviour response has been found to vary to some extent (roughly estimated to ±25%), although the general trend is consistent. Some of the variation is assumed to be caused by limitations in the methods of observation. Another factor which occasionally has been observed to reduce the magnitude of response, is an apparent "stimulus adaption" of the fish. In investigations undertaken in three different years in the same fjord area on the same fish species and at approximately the same time of the year, a high degree of consistency in the behavioural response has been observed.

4. DISCUSSION

The behavioural observations described in this report, focus attention on the possible impact that fish behaviour may have on the accuracy of acoustic abundance estimation.

There are two principal ways in which fish, through changes in behaviour, may bias the result of an abundance estimation. Firstly, the distribution of fish beneath a vessel may be changed in such a way that the acoustic beam of a ship echo sounder is unable to "hit" the fish, and secondly, the behaviour of the fish may vary in such a way that the target strength is difficult to predict.

The behaviour patterns we have described may operate in both ways, either via a varying density reduction and/or causing a depth dependant change in target strength to occur. The fundamental problem is that if the behaviour of the fish cannot be observed continuously and accurately, a considerable amount of _a priori_ information seems needed in order to obtain a sufficient level of accuracy of abundance estimation methods.

The species of fish which have been investigated in the current study are probably representative of the more common fish species. The avoidance response shown by cod in the Lofoten area, which is a very "noisy" environment, is remarkable and may be taken as an indication that most fish species will show some reaction when exposed to the influence of an approaching vessel. There are, however, still too few observations to make further comments upon the possible influence of daily rhythms, age, maturity stage etc. upon the magnitude of the response.

There is still a great need for more information regarding how often and on what depths density reductions beneath a surveying vessel may occur. It seems unlikely that technical solutions can be found to eliminate the "fleeing response" or to accurately observe its magnitude during routine survey work. Therefore, some form of "density correction" estimation may have to be incorporated into existing methods, but this presupposed that the necessary behaviour information is available.

A general conclusion to be drawn from the experiments is that it will be difficult to collect the necessary information about fish behaviour, but it seems also difficult to see how the necessary improvements in acoustic abundance estimation methods can be achieved without this information.

QUANTITATIVE ESTIMATIONS OF THE INFLUENCE OF FISH BEHAVIOUR ON ACOUSTICALLY DETERMINED FISH ABUNDANCE

by

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ABSTRACT

On the basis of a large number of observations of fish behaviour, a detailed description of fish reaction to an approaching vessel is presented. Based on this description a mathematical model is formulated which describes the reaction pattern and relates it to the hypothesis of the stimuli causing the reaction. The implications for acoustic back scattering from fish are analysed and discussed. The results show that a significant reduction in mean target strength, due to the reaction of the fish, is frequently to be expected. Finally a method of conversion of echoes into abundance is proposed which includes variables such as the depth distribution of fish, species characteristics and operation parameters related to the research vessel.

RESUME

Sur la base de nombreuses observations concernant les comportements du poisson, on présente une description détaillée des réactions du poisson à l'approche d'un bateau. Sur les bases de cette description, un modèle mathématique est formulé qui décrit la réaction et fait le rapport avec l'hypothèse des stimuli causant cette réaction. Les implications des rétro-diffusions acoustiques des poissons sont analysées et discutées. Les résultats montrent qu'une réduction considérable des index de réflexion moyens, due à la réaction du poisson est souvent prévisible. Finalement, une méthode de convertion des échos en abondance est proposée qui inclut des variables comme la distribution de profondeur du poisson, les caractéristiques spécifiques et les paramètres d'opération liés au bateau de recherche.

1. INTRODUCTION

Abundance estimation of fish by echo integration is based on the principle of the existence of proportionality between fish density and acoustic back scattering strength. Estimation of fish abundance is obtained by applying a simple linear relationship:

$$\bar{\rho} = C \cdot \bar{M} + d$$

Where ($\bar{\rho}$) is the average fish density along the course track, (C) is the "echo integrator output conversion coefficient", ($\bar{M}$) is the average echo integrator output and (d) is a threshold constant defining the registering sensitivity of the system (Midttun and Nakken, 1977).

The conversion coefficient (C) will depend both on the equipment characteristics and on the average target strength of the fish observed. The average target strength of the fish will be a function of fish species, fish size and of the spatial orientation distribution at the time of measurement (Nakken and Olsen, 1977; Foote, 1980).

Information regarding species and size of the fish registered can be obtained by simultaneous sampling, but information about the swimming orientation of free swimming fish is more difficult to gather. The few data are based upon observations of fish in an "undisturbed" condition (Olsen, 1971; Beltestad, 1974), but some recent work (Olsen, 1979) has shown that the presence of a vessel may substantially influence the behaviour of fish in its vicinity. The avoidance behaviour displayed by the fish may lead to considerable changes in both spatial and swimming orientation and this will affect the recorded target (Olsen et al., 1982).

Most of the methods commonly used in estimating echo conversion factors ("C-values") make no allowance for variations in target strength caused by changes in fish behaviour and therefore the level of precision is to a great extent unknown.

The degree of accuracy of the "echo trace counting method" (Midttun and Nakken, 1971) is highly dependent upon the proportion of fish in a "favourable" acoustic back scattering position. If avoidance behaviour in fish is depth dependent, which seems likely, the swimming orientation and the distribution will be affected by depth. Thus the proportion of fish in "favourable" acoustic back scattering positions may be depth dependent and this will have consequences for the calculated "C-value".

Measurements on caged fish (Johannesson and Losse, 1977) are only representative of fish in an "undisturbed condition" or of fish out of the region of behavioural influence of a surveying vessel.

Theoretical computations based on target strength measurements of fish having different orientations are inadequate until information of the spatial orientation distribution of fish under real surveying conditions can be incorporated into the model (Foote, 1979).

2. BEHAVIOUR MODEL

2.1 General model and acting stimuli

Olsen et al. (1982) describe avoidance behaviour of fish with the approach of a vessel. Avoidance begins with a slow turn in the swimming orientation, away from the vessel. As the vessel approaches more closely and is somewhat behind and above the fish, the swimming speed of the fish increases and swimming becomes more downwardly orientated.

Under some conditions, when fish are concentrated at relatively shallow depths, the behaviour may approach a stage of "panic fleeing" with the fish moving in all directions away from the vessel. The fish density then soon becomes significantly reduced, something which does not happen to any great extent when the fish display more moderate avoidance behaviour.

A number of factors are considered to be of importance in determining the "magnitude" of an avoidance reaction. Any attempt to generalize about reaction patterns for different species or fish in different biological situations, should be made most carefully. However, it may be possible to describe some general trends and identify important variables involved in such reaction patterns.

The dominating stimulus causing avoidance reactions in fish, on the approach of a vessel, is believed to be the low frequency noise generated, particularly, by the propeller of the vessel. In addition, to close range, the hydrodynamic pressure wave produced by the hull moving through the water, may have some effect. Visual stimuli are most probably of less importance except in some species which have been shown to be exceptional negative photo taxic (i.e. polar cod).

The magnitude of the noise stimulus acting on a fish will be related to the noise characteristics of the vessel, to the depth of the fish and to the vessel's distance from the fish. When the vessel approaches at a uniform speed, the noise level will increase, and the direction towards the noise source will change.

Directional hearing in fish has been shown to be related to the detection of "particle motion" (Schuijf and Hawkins, 1976). For a particular stimulus frequency, at some distance away from the source, the particle motion will be proportional to sound pressure. The "triggering" of an avoidance reaction by noise stimulation, has been shown to be related to the momentaneous increase in sound pressure or to the "steepness of the sound pressure gradient" (Olsen, 1969). This may lead to the conclusion that, although the level of the noise generated from the vessel is of importance, the main determining factor for the development of an avoidance reaction is more directly connected to the pressure gradient.

Let (P_F) be the pressure amplitude of the noise influencing a fish at the distance (R) from the noise source centre and (P_o) the assumed pressure amplitude at the source: $P_F = P_o/R$. With a vessel speed (v) and a fish positioned at a vertical angle α below the horizontal plane ahead of the vessel, the noise gradient can be expressed as:

$$\frac{dP_f}{dR} = -\frac{P_o}{R^2} \cdot \cos(90 - \alpha) \cdot (v \cos \alpha) \qquad (1)$$

$\cos(90 - \alpha)$ is an assumed approximation of the directivity characteristics of the stimulus source. ($v \cdot \cos \alpha$) is the vessel speed component in the direction of the fish.

Whenever a fish reacts to the approaching vessel by turning and swimming away, the magnitude of the stimulus the noise pressure gradient may be modified by the behaviour of the fish.

$$\frac{dP_f}{dR} = dP = -\frac{P_o}{R^2} \sin \alpha (v \cdot \cos \alpha - V_F \cos (\alpha - \beta)) \qquad (2)$$

where $v_F \cos (\alpha - \beta)$ is an expression of the swimming speed component of the fish in the direction away from the vessel. β is the tilt angle of the fish.

Fish which move directly away from the approaching vessel are "optimalizing" their effort in avoiding the "danger-signal".

The behaviour pattern which may be expected of fish in such situations would therefore be to move in accordance with this "principle". As the vessel approaches, the swimming speed is increased and the vertical swimming orientation gradually becomes more downwardly directed. The vessel speed component in the swimming direction of the fish then becomes less significant compared to the fish's own swimming speed and at a certain point the fish will "sense" that it is capable of "outrunning" the approach of the stimulus source. ($V \cos \alpha \approx V_F \cos(\alpha - \beta)$). It may therefore at this point start adjusting its swimming speed and/or tilt orientation accordingly. In addition, the capability of fish for directional discrimination of a noise source would probably mean that the gradual increase in "deviation from direct approach" would be registered by the fish.

In Fig. 1A and Fig. 1B are illustrated schematically the development of the three different stimuli which may influence fish during the approach and passage of a vessel. The effect of depth on the magnitude of the stimuli is evident in particular on the pressure gradient stimulus. If this stimulus is of major importance in determining the behaviour of fish, an avoidance reaction may be expected to tend "stabilize" before the propeller is passing as the stimulus is then already becoming reduced.

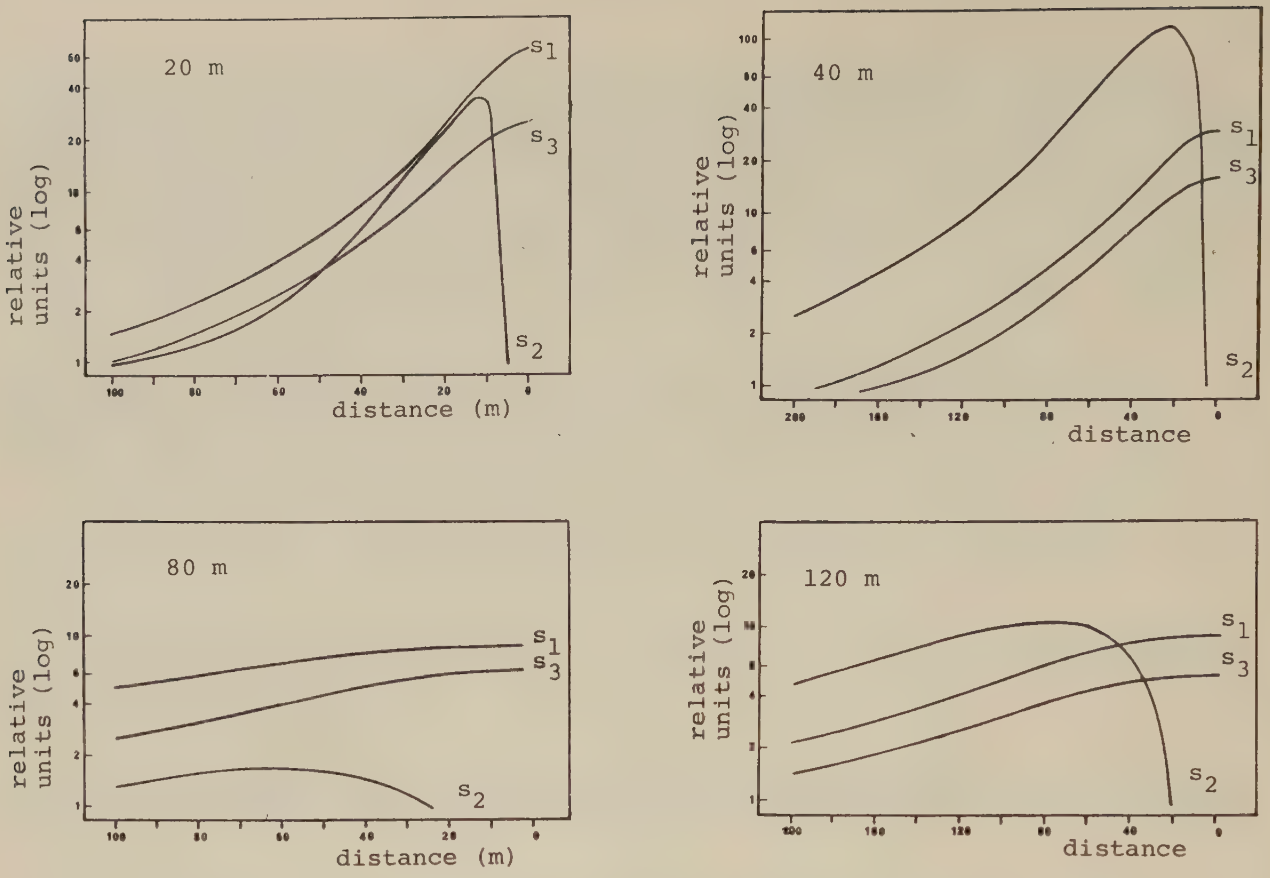

Fig. 1. Schematic illustration of the progression of the three different stimuli: S_1 = "Pressure amplitude", S_2 = "Pressure gradient" and S_3 = "Deviation from direct approach" in fish at different depths. (A): run by R/V "JOHAN RUUD" (300 tons) at 10 knots. (B): run by R/V "G.O. SARS" (1500 tons) at 12 knots.

2.2 Tilt angle estimation

Fig. 2 illustrates a generalized pattern of behaviour in fish at various depths and distances from the source when exposed to the noise stimuli from a passing vessel. The behaviour is expressed in terms of sequences of events of estimated mean tilt orientation. The estimation of tilt orientation are based on the assumption of the noise pressure gradient (or physical stimulus related to this gradient) being the stimulus determining avoidance behaviour ("S_2"). A second practical assumption is that fish before the vessel approaches is assumed to have a horizontal mean tilt orientation. The estimated pressure gradient threshold where an avoidance reaction is observed to start is illustrated as the "zone of influence" (I) and the threshold estimated when a "forced away orientated" swimming is observed is illustrated within the zone (F).

When fish are positioned in the zone where "panic fleeing" is observed to occur, a description of the swimming orientation is obviously more complicated. If fish are positioned shallowly enough, the pressure wave induced by the movement of the hull, becomes a strong stimulus. The sphere of influence will be considerably larger than the size of the vessel and the nature of this physical stimulus may be looked upon as one originating from a "Bernoulli source", where the pressure gradient will be reduced proportionally to $\approx 1/D^3$ where D is the depth.

A similar argument is valid for the stimulus reduction in a corresponding "near field" zone of the propeller. In addition, within this zone, an exponentional increase in "particle motion" amplitude in the low frequency noise stimuli is expected to occur. This would give a further dramatic increase in the strength of the stimuli to which the fish are exposed.

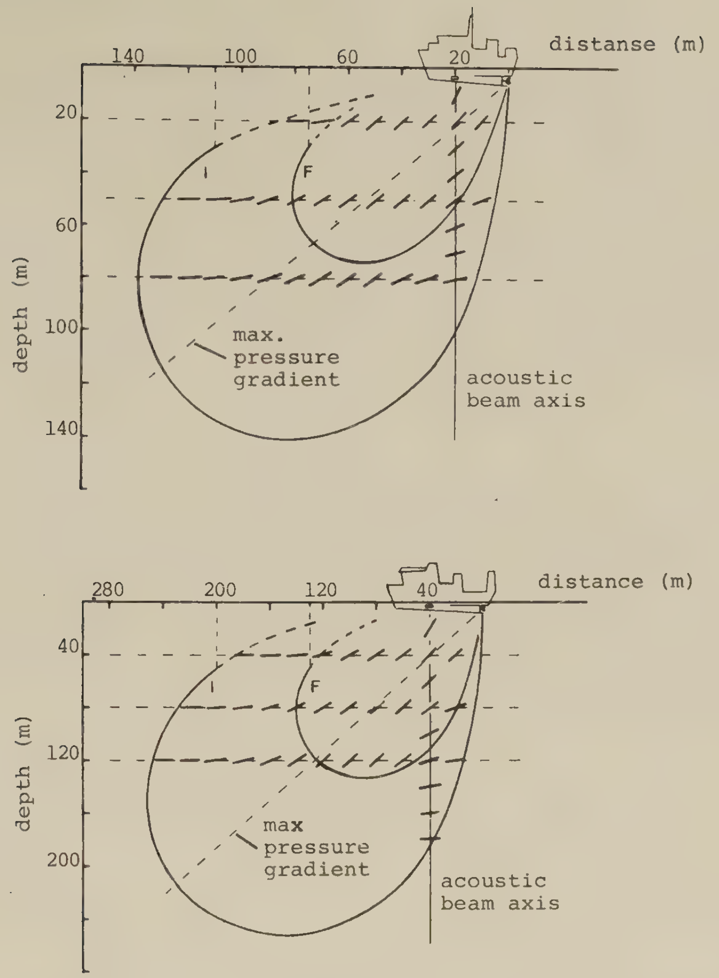

Fig. 2. Illustration of tilt orientation of fish at different depths and the field of influence of the "pressure gradient" stimulation when a vessel is passing above fish concentrations. A: R/V "Johan Ruud" running at 10 knots. B: R/V "G.O. Sars" running at 12 knots. (I): zone of first observed stimulus influence on the fish. (F): zone of assumed "forced" away orientated swimming of the fish observed.

The depth extension of the "near field zone" is defined to be the depth at which the stimulus originating from the vessel propeller becomes the dominating one compared to the "hull stimulus" (both as regards directional and gradient effect). This depth is assumed to correspond to the observed disappearance of "panic fleeing" in fish. If this depth is called (D_p) and the corresponding tilt orientation of the fish in the approximate area of the acoustic beam (β_p), the tilt orientation of a fish within the "near field zone" in the beam is assumed approximately estimated as:

$$\beta_D = \beta_p + \left(\frac{\pi}{2} - \beta_p\right) \left(\frac{D_p - D}{D_p}\right)^3 \qquad (3)$$

β_p is set equal to the vertical angle of a line through points of maximum increase in pressure gradient at different depths. The latter will be dependent on both vessel speed (v) and of the "avoidance" swimming of the fish (v_F).

When the vessel approaches the point of passage, the pressure gradient will increase more slowly and at a particular position the gradient will begin to reduce. At the same time the "deviation from direct approach" will increase rapidly and at some

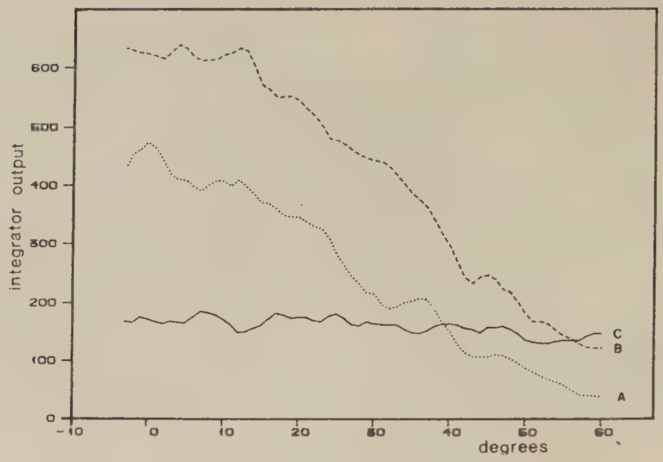

Fig. 3. Acoustic back scattering directivity pattern (38 kHz), in dorsal aspect of two groups of capelin swimming with equal horizontal orientation, (swimming speed ≈ 1/4 knot, $\bar{l}$=18,2 cm). A: 40 fishes with mean tilt of $-2^{\circ} \pm 2^{\circ}$, head up. B: 73 fishes with equal tilt orientation, and same swimming speed. C: 40 fishes swimming horizontally, mean tilt $-8^{\circ} \pm 10^{\circ}$, but random distributed and orientated within the cage. For experimental set up see Olsen *et al.*, 1982.

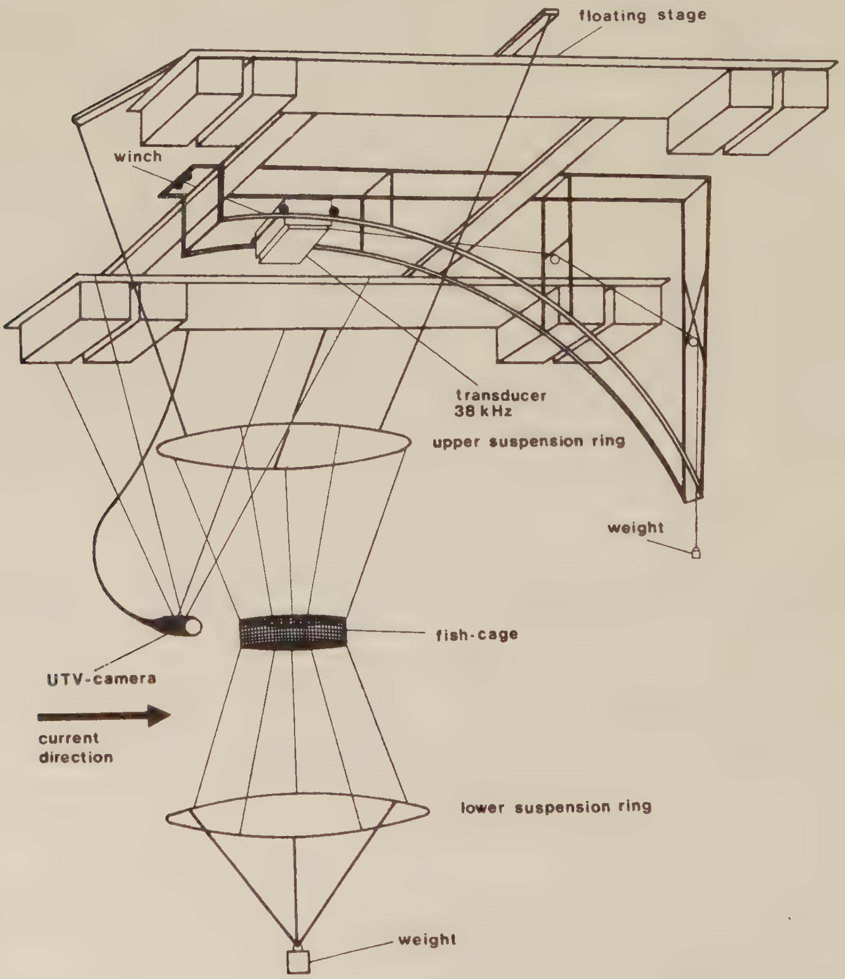

Fig. 4. Experimental arrangement used in measuring acoustic back scattering directivity pattern (38 kHz) in dorsal aspect of capelin ($\bar{l}$=18 cm). Aspect variation: -3°,+ 60°.

point the increase in downward tilting will stop. After a short while (estimated from video recordings to be in the order of 3-5 seconds), the behavioural response will start to decrease and this will have the effect of there being a certain depth zone where the change of tilt is minimal.

A similar argument is believed to be valid for estimation of the reduced tilt change at greater depth. The way the changes in echo recordings obtained during the passage of a vessel (Olsen, 1979, 1980) indicates that both the increase and reduction of tilt takes place through a process which is "smoothed out" both in time and at depth. If the pressure gradient is involved in the behaviour change the reduction in tilt at depth may therefore be assumed approximately inversely proportional to depth squared ($\approx 1/D^2$):

$$\beta_D = \beta_0 + (\beta_p - \beta_0)\left(\frac{D_0 - D}{D_0 - D_p}\right)^2 \qquad (4)$$

where (D_0) is the maximum depth of influence on the fish and β_0 is the mean tilt orientation of the fish in the undisturbed situation.

2.3 Fish density reduction

The fish density reduction beneath a surveying vessel, caused by the occurrence of a "radiation" of the fish out of the vessel path, has been assumed to be related, particularly, to the "near field stimulation" of the vessel. Both the "pressure wave stimulus" generated by the hull ($P_{HF} \propto L^2 v^2/R^2$, L=length, v=speed of the vessel) and the propeller generated "near field particle motion stimulus" ($PM \propto [1/R + 1/R^2]$) will have stimulus gradients which are inversely proportional to the cube of the depth ($\propto \approx 1/D^3$) and this reaction pattern is therefore strongly depth dependent.

The magnitude of density reduction observed in the acoustic beam, will be a function both of the pattern of fish reaction and of the length of time the reaction has progressed. The "reaction time" will depend on the transducer position in the hull, the speed of the vessel and of the magnitude of the stimulus.

The current available information does not allow a precise description of development of the observed density reductions. However, in the experiments using the R/V "Johan Ruud" and R/V "G.O. Sars" (Olsen et al., 1982), the observations of fish density reductions ($\Delta\rho$) have been shown to fit, with reasonable accuracy (± 25%), the linear equation:

$$\Delta\rho = -\frac{32}{\sqrt{L\cdot v}} D + 110$$

where $\Delta\rho$ is the percentage of density reduction of fish at a mean depth (D), (L) is the vessel length (m) and (v) is the speed of the vessel (m/s) and estimations of density reduction have therefore been attempted by use of this equation (Table 1).

Table 1. Estimation of reduced fish density with depth. (R/V "Johan Ruud" (300 tons) running at 10 knots above small herring at night and R/V "G.O. Sars" (1500 tons) running at 12 knots above adult capelin at night).

	Density reduction (%)	
Depth (m)	R/V "Johan Ruud"	R/V "G.O. Sars"
10	84	95
20	59	80
30	33	66
40	8	50
50	0 (44)	33
60		20
70		6
80		0 (73m)

2.4 Acoustic back scattering

In order to evaluate the impact of variable tilt in fish on acoustic back scattering, the back scattering directivity pattern must be known. In Fig. 3 is shown a plot of acoustic back scattering in dorsal aspect of a group of capelin ($\bar{L}$ = 18 cm), swimming with approximate equal horizontal orientation at a speed of about 1/4 knots (orientated within the natural current). The measurements are obtained by transmitting sound (38 kHz) at different dorsal aspect angles and by this method a "simulation" of a real tilt angle change of a group of fish is possible. Fig. 4 shows the experimental arrangement used.

The measurements were made with fish at 4m depth, but as the fish were adapted to 1m depth, the fish showed swimming behaviour suggesting they were somewhat "under bouyant". This resulted in an about $-2^{\circ} \pm 2^{\circ}$ (head up) tilt when the fish were swimming equally orientated against the current and a tilt of about $-8^{\circ} \pm 10^{\circ}$ when the fish were randomly horizontally orientated (without a current).

Table 2. Estimation of mean tilt angle of fish within the research vessel echo sounder beam (from equ. 2 and 3): (β_D). Ration of acoustic back scattering strength at and before vessel passage (from Fig. 3): ($k_{\sigma D} = \sigma_{\beta D}/\sigma_{\beta 0}$), ratio of fish density at and before vessel passage (from Table 1): ($k_{\sigma D} = \sigma_D/\sigma_{D0}$) and index of obtainable acoustic back scattering at vessel passage: ($k_{MD} = k_{\sigma D} \cdot k_{\sigma D}$).

R/V "Johan Ruud" (300 tons) running at 10 knots above small herring at night.

Depth (m)	(β_D)	$k_{\sigma D}$	$k_{\sigma D}$	k_{MD}
10	63	(≈0.04)	0.16	0.006
20	48	0.30	0.41	0.12
30	42	0.44	0.67	0.29
40	40	0.50	0.92	0.46
50	33	0.61	1.00	0.61
60	23	0.78	1.00	0.78
80	9	0.98	1.00	0.98
100	2	1.00	1.00	1.00

Table 3. R/V "G.O. Sars" (1500 tonns) running at 12 knots above adult capelin at night.

Depth (m)	(β_D)	$k_{\sigma D}$	$k_{\sigma D}$	k_{MD}
20	61	0.05	0.20	0.01
30	52	0.23	0.34	0.08
40	46	0.35	0.50	0.18
50	43	0.41	0.67	0.27
60	41	0.47	0.80	0.38
80	37	0.55	1.00	0.55
100	26	0.75	1.00	0.75
120	17	0.88	1.00	0.88
160	5	0.99	1.00	0.99

This difference in tilt may explain some of the difference in back scattering strength between equally orientated fish (A) and the same group swimming in an unorientated manner (C), but there still appears to be a ratio of about 2.5 : 1 in back scattering strength when fish are swimming in an orientated manner. By comparing the estimations of mean tilt orientation of fish within the acoustic beam (Fig. 4) of a surveying vessel, with the estimates of fish density reductions (Table 1) and the dorsal directivity back scattering pattern (Fig. 5), estimates of the relative acoustic back scattering strength of fish under the influence of a vessel can be made (Table 2 and Table 3).

When the ratio of the relative back scattering strength at a given depth interval during surveying to the relative back scattering strength in an undisturbed condition (k_{MD}) is known, the expected absolute echo integrator output (M_{abs}) can be estimated.

$$M_{abs} = M_{obs} \cdot \frac{1}{k_{MD}}$$

where (M_{obs}) is the observed echo integrator output in the given depth interval.

If (C_{ref}) is the echo conversion coefficient obtained from fish which are fully depth adapted, are swimming approximately equally horizontally orientated at constant depth and with a known tilt distribution (β_o ± st.d.), then the fish density may be estimated as:

$$\rho_{abs} = C_{ref} \cdot M_{abs} + (d)$$

(C_{ref}) may be obtained either through "cage calibration" experiments or perhaps estimated theoretically from an "echo trace counting" experiment if the tilt angle distribution and the "real" sampling volume of the echo sounder beam at all different depths are known.

3. DISCUSSION

The proposed conversion model is intended to incorporate some of the important factors related to fish behaviour into the echo integrator method. Other important factors, such as acoustic "shadowing" in dense fish concentrations and surface/bottom distributions of fish ought to be considered in further investigations.

The model is to be regarded as a preliminary one and once more of the basic information has been collected, a more precise description of the behavioural events should be possible and a more complete version of the model proposed.

One great problem in the proposed model is the necessary "generalization" of behaviour in order to obtain what is regarded as "typical" pattern of behaviour of a fish species in a particular biological situation. In further developments of the method, this approximation will be greatly improved if more extensive information can be obtained. The most promising available technique seems to be to measure the doppler shift in the echo signals and combine this with single fish trace from analyzis and target strength data. This may allow a continuous monitoring giving information as to whether or not vertical migration of the fish is occurring.

A second difficulty in the model is to obtain a more precise estimation of the density reduction beneath the vessel. The importance of this is, as demonstrated, increased when the fish are more shallowly distributed. Adequate information relating to this problem can only be obtained by conducting experiments under various conditions.

List of symbols

A:	Distance at surface from noise source (propeller) (m).
D:	Depth (m).
D_0:	Max. depth of influence on the fish (m).
D_p:	Max. depth of "near field zone" (m).

R: Distance from noise source (m). $R = \sqrt{A^2 + D^2}$

P_0: Noise pressure amplitude at source.

P_F: Noise pressure amplitude at the fish.

dP_F/dR: Noise pressure gradient.

v: Vessel speed (m/s).

v_F: Swimming speed of fish (m/s).

α: Vertical angle below horizontal plane (degr.).

"S_1": "Pressure amplitude stimulus" ("S_1" $= P_F = \frac{P_o}{R}$)

"S_2": "Pressure gradient stimulus" ("S_2" $= \frac{dP_F}{dR} = - \frac{P_o}{R^2}$)

"S_3": "Deviation from direct approach stimulus" ("S_3" $\propto \frac{V \cdot D}{D^2 + A^2}$)

β_0: Mean tilt angle (degr.) of fish in the undisturbed situation.

β_p: Mean tilt angle of fish at max. depth of "near field zone".

β_D: Mean tilt angle of fish at a certain depth.

P_{HF}: Pressure wave stimulus generated by the hull.

PM: "Near field particle motion" generated by propeller.

L: Vessel length (m).

$\bar{l}$: Mean fish length (cm).

Δp: Percentage of density reduction of fish at a certain depth.

σ_{β_0}: Acoustic back scattering cross section, undisturbed.

σ_{β_D}: Acoustic back scattering cross section, disturbed.

k_{σ_D}: Ratio of acoustic back scattering cross section disturbed/undisturbed.

$\bar{\rho}$: Average fish density along the course track.

ρ_{abs}: Absolute fish density (average value).

ρ_D: Fish density, disturbed.

ρ_{D_0}: Fish density, undisturbed.

k_{ρ_D}: Ratio of fish density disturbed/undisturbed.

K_{MD}: Index of acoustic back scattering strength.

$$(k_{MD} = k_{\sigma_D} \cdot k_{\rho_D})$$

$\bar{M}$: Average echo integrator output.

M_{abs}: Absolute integrator output (average value).

M_{obs}: Observed echo integrator output (average value).

C: Echo integrator output conversion coefficient (Length and species dependent, established by standard methods).

C_{ref}: Echo conversion coefficient obtained from fish which are:

1. Fully depth adapted.
2. Approximately equally horizontally orientated.
3. With known tilt distribution (β_o ± st.d.) Length and species dependent.

d: Threshold constant (registering sensitivity of the echo integrator system used).

SOME OBSERVATIONS ON FREQUENCY DEPENDENT BACK SCATTERING STRENGTH

by

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ABSTRACT

In extensive fish resources surveys off the coasts of Burma in 1980 and West-Africa in 1981, observations of echo intensity from midwater scatterers were obtained simultaneously from two echo sounder-integration systems based on sound frequencies of 38 kHz and 120 kHz respectively. The analysis of the data include the classification into broad categories of the types of scatterers based on fishing experiments and on the characteristics of the echo recordings. The two main categories are: fish in schools and scattering layers, and plankton. Integrator deflection was used to estimate the mean volume back scattering strength $\bar{S}v$ of samples of classified scatterers. Plots of paired estimates of $\bar{S}v$ were made and consistent differences were found relating to the type of scatterer. For fish the values of $\bar{S}v$ were found to be higher on the 120 kHz system, while the opposite was the case for plankton scatterers.

The results indicate that for fish of the size ranges studied (about 10-25 cm) the volume back scattering strength and by inference the target strength of individual fish is frequency dependent and its value may be roughly 4 dB higher at 120 kHz than at 38 kHz. Results are quoted of experimental work on target strength of fish which indicate that a 2-3 dB higher target strength should be expected at 120 kHz than at 38 kHz.

The phenomenon of difference in back scattering strength of fish and plankton has proved to be a useful additional tool for the broad classification of scatterers and there would seem to be a considerable potential for further development of its application.

RESUME

Au cours de prospections vastes effectuées au large des côtes de Burma en 1980 et d'Afrique de l'ouest en 1981, des observations d'intensité d'écho émis par des corps différents en pleine eau étaient obtenues simultanément par deux systèmes d'écho-intégration de 38 kHz et 120 kHz respectivement. L'analyse des données comprend le classement par larges catégories des types de "corps diffusants" basé sur des pêches de contrôle et les caractéristiques des échos enregistrés. Les deux principales catégories sont: les poissons en bancs ou en couches diffusantes et le plancton. La déflection de l'intégrateur a été utilisée pour estimer l'index moyen de rétrodiffusion volumique $\bar{S}v$ pour des échantillons de différents types de corps diffusants. La représentation graphique des paires d'estimations $\bar{S}v$ obtenues avec les deux fréquences fait ressortir des différences systématiques liées au type de corps diffusant. Pour les poissons, les valeurs de $\bar{S}v$ se sont révélées plus élevées à 120 kHz, tandis que dans le cas du plancton ce fut le contraire.

Les résultats indiquent que pour les tailles de poissons étudiés (environ 10-25 cm) l'index moyen de rétrodiffusion volumique, et par conséquent l'index de réflexion d'un poisson isolé, dépend de la fréquence et que sa valeur peut-être plus élevée d'environ 4 dB à 120 kHz qu'à 38 kHz. Des résultats d'expériences effectuées sur l'index de réflexion sont cités, qui indiquent que l'on obtient un index de réflexion plus élevé de 2 à 3 dB à 120 kHz qu'à 38 kHz.

Le phénomène de différence de la rétrodiffusion entre les poissons et le plancton se révèle être un outil supplémentaire pour la classification grossière des corps diffusants. Il semble exister des possibilités considérables de développement ultérieur de son application.

1. INTRODUCTION

In an intercalibration exercise of the two echo sounder-integration systems at 38 kHz and 120 kHz available on the R/V "Dr. Fridtjof Nansen" during a survey off Sri Lanka in 1979 (Blindheim et al., 1980) it was found that the ratios of the integrator deflections varied with a factor of up till five even when averaging the observations over five nautical miles sailing. It was noted during the cruise that the 38 kHz system gave high integrator readings for plankton scatterers. In a similar intercalibration test during the start of a survey off Burma (Strømme et al., 1981) it was found that the two systems gave nearly equal outputs for small pelagic fish scatterers, while plankton layers contributed much more to the 38 kHz than to the 120 kHz system. In a number of later surveys with the "Dr. Fridtjof Nansen" this apparent difference in sensitivity to type of scatterer has been used as an aid in the rough identification of targets by running the two systems in parallel. A more detailed analysis of such simultaneously collected observations from surveys off Burma in April 1980 and off West-Africa in September 1981 is presented in this paper.

2. INSTRUMENTS, METHOD OF ANALYSIS AND DATA

The settings of the instruments and the performance data based on calibrations on standard spheres are shown in Appendix I. The difference in performance of the 38 kHz sounder between the two survey periods is due to a change undertaken in the amplifier gain.

The material analysed included:

Echo-sounder diagrammes (0-100 m) 120 kHz and 38 kHz.

Integrator-write-outs 120 kHz and 38 kHz.

Acoustic log-sheets with mean 5-mile values of integrator deflection pr nm. for (a) total, (b) plankton, (c) pelagic fish.

The echo-recordings were classified in the following categories:

A: Fish in schools, no plankton on either diagrammes (or only very faint on 38 kHz).

B: Fish in scattering layer, no plankton on either diagrammes (or only very faint on 38 kHz).

C: Mixture of fish echoes and plankton layers (fish in schools or single fish traces).

D: Plankton scattering layers only.

The integrator deflections on the 38 kHz and 120 kHz systems were recorded for the above categories on a per nautical mile basis, either averaging the values over 5 nm, or using a shorter distance over which the echo-diagrammes indicated a recording which represented one of the four categories listed above.

Observations were discarded on the following criteria:

when bottom echoes or other echoes deriving from one of the other sounders appeared in the recordings

where the bottom-stop discriminator had been set too low and bottom had been integrated

where dense schools had been recorded with the bottom-stop function in use in the same channel.

For the Burma data no distinction was made between fish in schools and fish in scattering layers.

A few sets of observations are available of fish recordings during trawling (Burma) and of bottom (West-Africa).

The total number of paired observations analysed in this way includes about 570 from the survey off Burma and 600 from West-Africa.

The mean volume back scattering strength were calculated for these data according to

$$\bar{S}v = 10 \log I - A + \bar{V}_{01} - 10 \log \Delta R + C_1 + C_2$$

where

I - integrator output reading (mm)

A - integrator gain (dB)

$\bar{V}_{01}$ - integrator performance constant for QM - MKII $\bar{V}_{01} = -1.90$ dB

ΔR - recording interval. All observations are referred to 10 m interval

C_1 - echo sounder constant

C_2 - echo sounder settings constant

The application is shown in Appendix I.

3. RESULTS

All results are presented in diagrammes but the data are available in tables.

3.1 The Burma survey

After having discarded some data in accordance with the criteria listed above 571 sets of observations could be classified as follows: 123 referring to fish in school or scattering layers, 72 referring to plankton and 376 referring to a mixture of fish and plankton. The mean volume back scattering strength was calculated from the integrator deflections and all pairs of observations of the two categories fish and plankton are shown plotted in Fig. 1a.

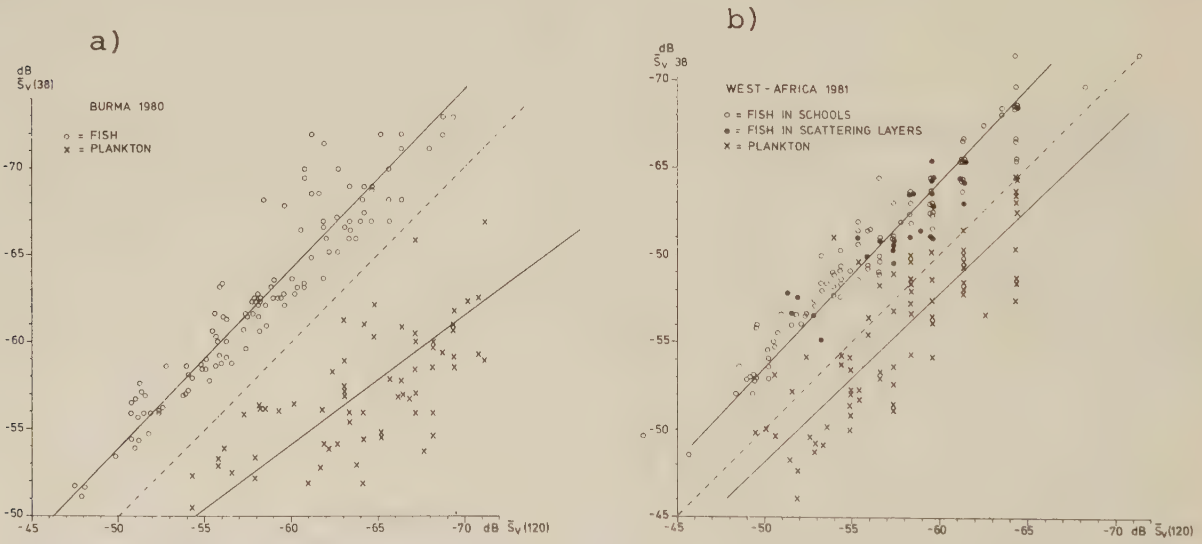

Fig. 1. Plots of paired observations of mean volume back scattering strength from the 38 kHz and 120 kHz systems for fish and plankton, and the functional regression lines, Burma 1980 (left) and West-Africa 1981 (right).

Assuming the mean volume back scattering strength to be independent of the frequency or any other differential character of any of the systems, plots of paired estimates of $\bar{S}v$ would be expected to follow a simple linear relationship along the midline (bi-sector) $\bar{S}v_{38} = \bar{S}v_{120}$ with some minor bias or variance caused by measurement error etc. The observations demonstrate, however, consistent differences of $\bar{S}v$ between the two systems related to the type of scatterer. All "fish-observations" are distributed well above the bi-sector while those for plankton are found below. The fish estimates show a high correlation (r = 0.95), the functional regression being:

$$\bar{S}v_{38} = 1.04\ \bar{S}v_{120} - 1.69$$

The plankton observations are less strongly related (r = 0.69) described by the functional regression

$$\bar{S}v_{38} = 0.74\ \bar{S}v_{120} - 9.64$$

Observations of back scattering from an assumed mixture of plankton and fish are not shown in Fig. 1a, but has a distribution covering a wide intermediate field.

Another way of presenting the findings is shown in Fig. 2a which demonstrates the frequency distributions of the differences $\bar{S}v_{38} - \bar{S}v_{120}$ for each of the pairs of observations for fish and plankton. For fish the values are grouped almost normally around a grand mean of -4.2 dB. For plankton the values range from about 2 dB to 13 dB with no main grouping and a mean of about 7 dB.

An attempt was made to regroup the mixed recordings containing both plankton and fish in four subgroups: fish with some plankton, more fish than plankton, about same proportions and more plankton than fish. The distribution of these groups when presented as in Fig. 2 demonstrated a clear successive transfer from the left towards the right of the diagramme.

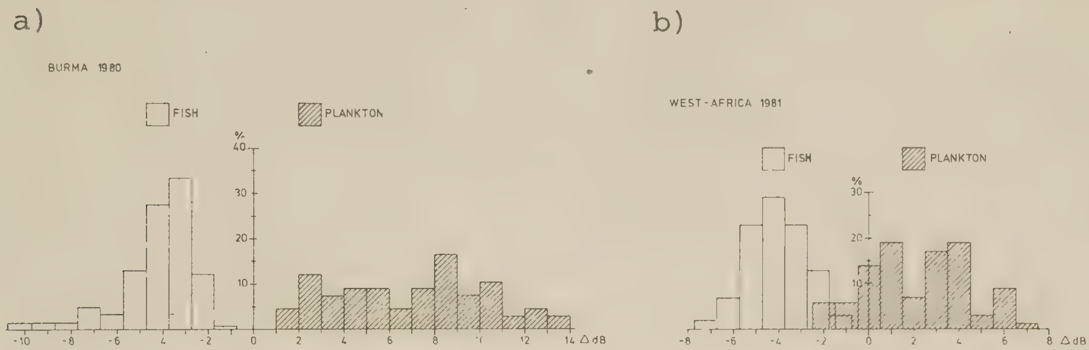

Fig. 2. Frequency distributions of the differences $\Delta = \bar{S}v_{38} - \bar{S}v_{120}$ for each set of observations for fish and plankton, Burma survey 1980 (left) and West-Africa 1981 (right).

Some observations derive from measurements in a gated channel in front of the gear during trawling. The difference $\bar{\Delta} = \bar{S}v_{38} - \bar{S}v_{120}$ for these sets of data were as follows: -2.9, -4.4, -3.3, -3.3, -4.4, -4.3, and -4.4 dB with a mean of -3.9 dB thus confirming the values found for the category classified as fish.

3.2 The West-Africa survey

The 602 sets of estimates available after discards could be classified into 123 containing fish in schools and scattering layers only, 68 containing plankton only and 411 with a mixture of fish and plankton. Fig. 1b shows the plots of the fish and plankton observations. Fish in schools and in scattering layers were originally analysed separately, but as no difference could be seen in their distribution a joint analysis has been made. The pairs of fish estimates show a high correlation with r = 0.96 the functional regression being

$$\bar{S}v_{38} = 1.07\ \bar{S}v_{120} - 0.06$$

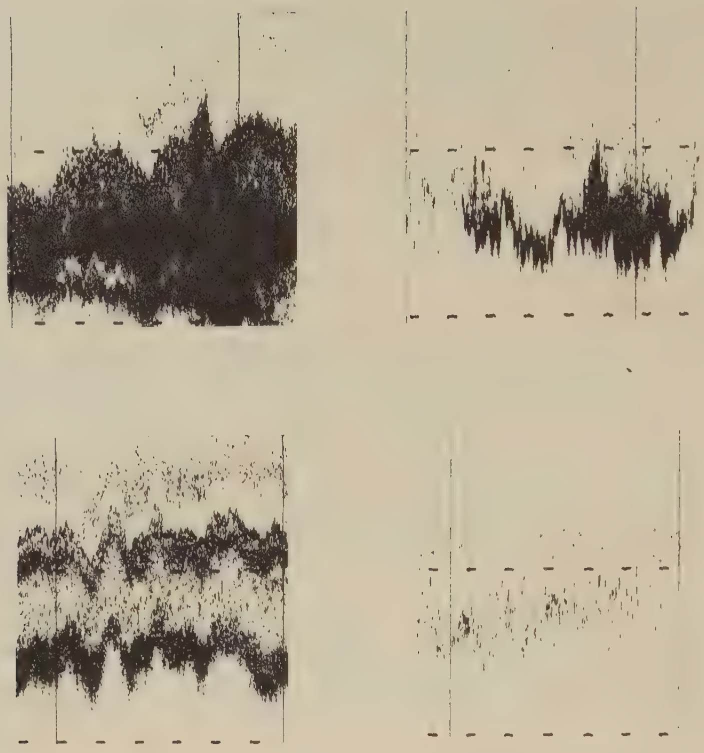

Fig. 3. Sections of echo-diagrammes of mixed distributions of plankton with fish in schools (upper pair) and with single fish traces (lower pair) demonstrating the higher back scattering strength of plankton on the 38 kHz system (left), West-Africa 28/9/81.

Also the plankton category observations are reasonably well correlated with r = 0.85 the regression being

$$\bar{S}v_{38} = 0.96\ \bar{S}v_{120} - 0.22$$

Fig. 2b shows the distribution of the values $\bar{\Delta} = \bar{S}v_{38} - \bar{S}v_{120}$. Fish is grouped regularly around a mean value of about -4 dB, while the distribution of the plankton values are irregular and range from -1 to +7 dB with a mean of 2.2 dB.

The distribution of the $\bar{\Delta}$ -values for recordings containing a mixture of fish and plankton covers almost the whole range shown in Fig. 2b and shows several modes.

A few observations are available of bottom back scattering strength. They represent 3 x 1 nm of cruise tracks and the difference $\bar{\Delta} = Sv_{38} - Sv_{120}$ were: -1.2, -0.74, -0.96 with a mean value of -0.96 dB.

4. DISCUSSION

Firstly we would like to stress that the data analysed in this paper represent the processed means of a very large number of single measurements probably of the order of one million for each of the areas. The "fish-only"-measurements comprise about 20 per cent of this and "plankton only" about 12 per cent.

The main finding is the demonstration of consistent differences in mean volume back scattering strength $\bar{S}v$ between the 38 KHz and 120 KHz systems, and that the differences found seem to be related to the type of scatterer. In the two different areas and under different working conditions the mean volume back scattering strength from targets classified as fish was consistently higher for the 120 KHz system than for that operating at 38 KHz, the mean difference being about 4 dB (4.2 and 4.1 dB for each of the surveys).

Plankton scatterers, on the other hand, were found to give higher values of mean volume back scattering strength on the 38 KHz than on the 120 KHz system with a mean of 7.0 dB in the Burma survey and 2.2 dB in the West-Africa survey. While the fish differentials ranged over an interval of only about 4-5 dB, those for plankton had a much wider spread and ranged over about 10 dB.

The general observation that a 120 KHz system is more "sensitive" to fish scatterers and a 38 KHz system more effected by plankton scatterers has also been experienced by other researchers when conducting fish surveys in West-African waters, (Miquel et al., 1981 and E. Marchal, personal communication).

On the basis of our findings and their general confirmation by other results we find it reasonable to conclude that this is a demonstration of a frequency dependence of volume back scattering strength of the various types of targets.

Frequency dependent target strength of fish has been reported from experimental work. For dorsal aspect target strength of fish in the range $0.8 < L/\lambda < 20$ McCartney and Stubbs (1971) found the relation $T = 24.5 \log_{10} L - 4.5 \log_{10} \lambda - 26.4$. The types of fish in our surveys, mainly small pelagic sardines and sardine-like fish of about 10 to about 25 cm length, would fall within this range. The above equation would give about 2 dB higher target strength on 120 KHz than on 38 KHz. Goddard and Welsby (1977) found a largely similar relationship based on experiments with 10 KHz, 30 KHz and 100 KHz frequencies. Applied to our frequencies there would be a 3 dB higher target strength at 120 KHz than at 38 KHz. The approximately 4 dB difference found in our data thus seems to be in reasonable accordance with these experimental results.

The much wider spread found in the differences in back scattering strength from scatterers classified as plankton is explained by the variety of organisms included in this category e.g. phytoplankton, medusae, copepods, fish eggs and -larvae, post-larvae etc. The survey programmes did not include plankton sampling and only incidental samples were sometimes obtained in the fine-meshed net of the midwater trawl. Further identification is therefore not possible. One should note that the observations relate to tropical, sub-tropical and warm temperate regions and the organisms found there. Similar studies from other areas are not known to us, but O. Nakken, (personal communication) found that krill (Euphaucids) showed higher back scattering on a 120 KHz system than on 38 KHz.

In the regions from which these data have been obtained the phenomenon has already proved to be a valuable additonal tool for the broad classification of scatterers and in the quantitative assessment of the fish biomass. Fig. 3 shows examples of echo diagrammes from the two systems which demonstrate the practical use in identification of fish scatterers. The recorder gains were adjusted to show equal marking of fish traces.

Another consequence of the frequency dependent back scattering strength from different types of scatterers is that intership calibration at two different frequencies must be expected to give highly variable results depending on the type of scatterer. Even at the same frequency intercalibrations should only be made on "clean" fish distribution.

In general there would seem to be a considerable potential for further development of using these phenomenons with the aim of finding non-subjective methods for classification of scatterers.

ACKNOWLEDGEMENT

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APPENDIX I

Calibration data and the calculations of the volume back scattering strength. R/V "Dr. Fridtjof Nansen", Burma, April 1980 and West-Africa, September 1981).

I. Echo-sounder settings

EKS-38:	BURMA	W-AFRICA
EXT.TRANSM.	(2.5 kW)	2.5 kW
Pulselength	0.6 ms	0.6 ms
TVG	20 log R	20 log R
Gain	0 dB	-20 dB
Rec. gain	1	6
EKS-120:		
TRANSM.	1/1	1/1
Pulselength	0.6 ms	0.6 ms
TVG	20 log R	20 log R
Gain	0 dB	0 dB
Rec. gain	3	3

Integrator settings

QM-MKII	BURMA	W-AFRICA
Gain	10 dB	20dB
scale	x 10	x10
ΔR	10 m	10m
Thresh.	8	0.8
QM-MK II		
Gain	20 dB	10 dB
scale	x 10	x10
ΔR	10 m	10 m
Thresh.	8	0-0.5

II. Performance data

	EKS 38		EKS 120	
	BURMA	W-AFRICA	BURMA	W-AFRICA
SL + VR (dB)	132	139	102.8	103
$20 \log R_0 + 2\alpha R_0$ (dB)	64.5	64.5	49	49
$10 \log \frac{cT}{2}$ (dB)	- 3.5	-3.5	- 3.5	-3.5
$10 \log \Omega_0$ (dB)	- 20	-20	- 18	-18
C_1 (dB)	- 44	-51	- 32.3	-32.5
C_2 (dB)	0	21.5	0	0
A (dB)	20	30	30	20
$\bar{V}_{01}$ (dB)	1.9	1.9	1.9	1.9
ΔR (m)	10	10	10	10

III. Volume back scattering strength calculation

$$\bar{S}_v = \bar{V}_0 - A + C_1 + C_2 \quad , \quad \bar{V}_0 = 10 \log I - 10 \log \Delta R + \bar{V}_{01}$$

$$C_1 = -(SL+VR) + 20 \log R_0 + 2\alpha R_0 - 10 \log \frac{CT}{2} - 10 \log \Omega_0$$

For EKS-38 and QM: $\bar{S}_v = 10 \log I - 75.90$ dB (Burma)

$\bar{S}_v = 10 \log I - 71.40$ dB (W-Africa)

For EKS-120 and QM: $\bar{S}_v - 10 \log I - 74.20$ dB (Burma)

$\bar{S}_v - 10 \log I - 64.40$ dB (W-Africa)

IV. Difference between volume back scattering strength for two frequencies

$\Delta = Sv_{38} - Sv_{120}$

HYDROACOUSTIC ASSESSMENT IN HIGH DENSITY FISH SCHOOLS

by

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ABSTRACT

The usual techniques of hydroacoustic assessment are based upon a single scattering hypothesis, that is, the acoustic signal arriving at and reflected by each fish is unaffected by any other fish. For schools of fish which are dense or large in extent in the direction of acoustic propagation, this hypothesis is not valid. This paper presents modifications of the standard methods which can be applied when the single scattering hypothesis is not valid.

RESUME

Les techniques habituelles d'évaluation hydroacoustique sont basées sur l'hypothèse d'une seule collision suivant laquelle l'onde acoustique arrivant sur un poisson n'est pas affectée par d'autres poissons. Pour des bandes de poissons qui sont denses ou qui s'étendent dans la direction de la propagation acoustique, cette hypothèse n'est pas valable. Ce travail présente des modifications qui peuvent être faites pour améliorer l'évaluation de la densité quand l'hypothèse d'une seule collision n'est plus valable.

1. INTRODUCTION

Current methods of hydroacoustic fisheries assessment explicity or implicitly assume that the interaction of one fish with the acoustic field does not affect the acoustic field impinging on any other fish. Although this is clearly invalid, it is usually a reasonable assumption when the collection of fish is neither dense nor of large extent in the direction of acoustic propagation. In this paper we investigate some methods for improving fish density estimations when this simple scattering model leads to significant estimation errors.

The simple scattering assumption leads to the conclusion that the acoustic power received at a particular time due to the reflection of a transmitted acoustic pulse is directly proportional to the number and size of fish at a corresponding depth independent of numbers at intermediate depths. As a consequence, the "echo-integration" method of density estimation has been developed and utilized extensively. This method will be used as a basis of comparison with other techniques developed here which also use the received power measurement as a foundation for determining fish densities. The echo integration technique depends only upon the backscattering characteristics of the fish, whereas in those cases where the simple scattering assumption cannot be validly made, a more complete scattering description must be employed. Consequently, we turn now to a study of scattering by an individual fish as a first step towards a formulation of improved techniques of estimating numbers density in fish schools.

2. SCATTERING BY INDIVIDUAL FISH

2.1 Some definitions

Given a continuous, plane pressure wave of frequency f_o, with unit intensity, traveling in a direction specified by the unit vector $\hat{i}$, impinging on a reflecting body (fish), the fundamental scattering quantity is the differential cross-section $\sigma_d(\hat{o},\hat{i})$. It is defined as the amount of power per unit solid angle scattered into the direction of the observation, $\hat{o}$, per unit impinging intensity. The value of the parameter depends upon f_o and the size and structure of the fish and its orientation relative to $\hat{i}$ and $\hat{o}$. The more commonly utilized backscattering cross-section $\sigma_b(\hat{i})$ is defined as

$$\sigma_b(\hat{i}) = 4\Pi\sigma_d(-\hat{i},\hat{i}) \tag{1}$$

and the target-strength is defined as

$$TS(\hat{i}) = 10 \log_{10} \sigma_d(-\hat{i},\hat{i}) \tag{2}$$

The scattering cross-section provides a measure of total power scattered.

$$\sigma_s(\hat{i}) = \int_{4\Pi} \sigma_d(\hat{o},\hat{i})\,d\Omega_o \tag{3}$$

Some of the incident acoustic energy may be absorbed rather than scattered. A measure of this effect is the absorption cross-section.

$$\sigma_a(\hat{i}) = \frac{\text{absorbed power}}{\text{incident intensity}} \tag{4}$$

Finally, the total power scattered and absorbed is proportional to the extinction cross-section, $\sigma_t(\hat{i})$.

$$\sigma_t(\hat{i}) = \sigma_s(\hat{i}) + \sigma_a(\hat{i}) \tag{5}$$

One last quantity to be defined is the asymmetry factor $\bar{\mu}$, which is a measure of the directivity of the differential cross-section.

$$\bar{\mu}(\hat{i}) = \frac{1}{\sigma_s(\hat{i})} \int_{4\Pi} \sigma_d(\hat{o},\hat{i})\cos(\hat{o}-\hat{i})\,d\Omega_o \tag{6}$$

The quantity will range from zero for isotropic (small) scatterers to near unity for scatterers which are large compared to the wavelength.

2.2 Cross-section behavior and modeling

The acoustically important features of a "typical" swimbladder-bearing fish are the swimbladder which is virtually 100% reflective in water, and the backbone complex, whose amplitude reflectivity in seawater has been measured between .24 and .76, is an influential scattering structure at higher frequencies and broadside incidence (Haslett 1970). Its proximity to the swimbladder contributes to the interference phenomena observed during measurements of target strength. The soft tissues which comprise the remainder of the body have acoustic characteristics near those of the water and although not major contributors to scattering, possess properties responsible for absorptive losses.

With respect to scattering, the range of frequencies can be divided into four intervals. The Rayleigh region is for $b/\lambda << 1$, where $2b$ is the maximum dimension of the dominant scattering struction (swimbladder) and λ is the acoustic wavelength. In this region the scattering is nearly isotropic, absorptive losses are negligible, and σ_b and σ_t will be proportional to λ^{-4}. In the next small interval, $b/\lambda \approx 1$, the resonance region, the swimbladder is stimulated to a resonance condition and re-radiates and absorbs considerably more power than is predicted by the Rayleigh approximation. (Love 1978, McCartney 1971). For both Rayleigh and resonant scattering, the orientation of the fish relative to the direction of incidence has only a minor effect on the cross-section behavior.

In the geometric optics region, $a/\lambda >> 1$, where $2a$ is the minimum linear dimension of the swimbladder, half of the scattered power will be reflected in various directions from the curved surfaces. The other half will be confined to a narrow angular region in the forward direction, interfering with the incident wave to create a shadow immediately behind the fish. At high frequencies, absorption due to the tissues becomes significant also. Estimates of σ_a can be obtained from measured power absorption rates from muscle and various organs. Schwan (1969), for example, shows rates for mammalian tissues of $.5 \times 10^{-6} f_o$ dB/cm.

For fish size-to-wavelength ratios which do not fit into the above categories, accurate predictions of cross-sections are difficult. In this transition region, values of σ_t and σ_b oscillate about the asymptotic values predicted by the geometric optics approximations.

2.3 Cross-section measurement

Because of questions involving the validity of scattering measurements obtained using dead, stunned, or otherwise anaesthetized fish, a technique was devised for measuring dynamic cross-section of live, freely-swimming fish. The apparatus shown in Figure 1 was placed in a large tank and three transducers were arranged for measurement of σ_t and σ_d. Rainbow trout (14-16.5 cm) were convinced to swim slowly through an acoustically transparent passageway between holding tanks during the tests. A 100 μsec, 241 kHz pulse was transmitted every .1 sec. Received signals were peak detected, and the largest or smallest of the scattered signals was recorded for differential or extinction cross-section measurement respectively.

The measured values fell within the range expected and it was concluded that for the geometric optics region the fish could be reasonably represented by an acoustically soft ellipsoidal model of dimension 0.3L x 0.05L x 0.07L where L is the total length of the fish (Maxwell 1980).

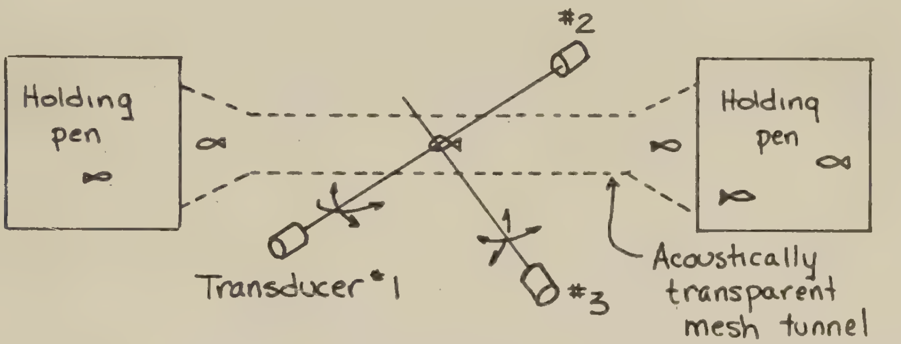

Figure 1. Experimental system for measuring scattering parameters. The transducers, at a fixed distance from the center of the tunnel, can be varied in angular orientation.

3. SCATTERING BY SCHOOLS

3.1 Theories of scattering

The theories of scattering may be categorized under one of two general classifications. Analytic theories deal directly with pressure or potential fields and their statistical properties in time and space. Although possessing little practical applicability in their exact forms, approximations based on these theories have been successfully used in a variety of remote sensing problems. (Ishimaru 1978, deWolf 1971, Bremmer 1976). The second category includes heuristic theories which assume that no correlation exists among the fields produced by the different scatterers in a random medium. By requiring, for example, that uncertainty in the location of any fish within a school be greater than a wavelength, then it can be assumed that the addition of acoustic intensities, rather than fields can be used to characterize the scattering. Approximations based on heuristic formulations have been widely used in remote sensing problems (Haslett 1970, Reynolds 1976, Shimizu 1979, 1980).

Neither heuristic theories which account for multiple scattering nor exact analytic formulations can be solved exactly for all combinations of scatterers, geometries, frequencies, pulse durations, densities, etc. Although it would be desirable to find a single theory which would provide a school biomass or density estimate for all cases of interest, this has not been possible. It thus becomes necessary to rely on a group of suitable approximations which are discussed in the following sections.

A quantity which is an important gauge in determining the limits of usefulness of various approximations is the optical distance τ defined as

$$\tau(x) = \int_0^x \int_w n(x',w)\sigma_t(w)\,dw\,dx' \qquad (7)$$

The integral above can be considered to yield the average accumulated extinction cross-section per unit insonified area at a depth x. The function $n(x,w)$ is a depth dependent probability density function for the random variable w which includes fish density, size, species, orientation, etc. As a clarification of (7), suppose all the randomness of the fish except numbers density is independent of depth, x. Then, integration with respect to w will yield $\bar{\sigma}_t$, the average extinction cross-section, and (7) reduces to

$$\tau(x) = \int_0^x \rho(x)\bar{\sigma}_t\,dx \qquad (8)$$

where $\rho(x)$ is the numbers density as a function of depth. If the density is uniform between $x=0$ and $x=d$, then the optical distance (or thickness) at depth d is

$$\tau(d) = \rho\bar{\sigma}_t d \qquad (9)$$

The dimensionless quantity τ is an indicator of the extent to which the incident wave has encountered scatterers in the intervening volume. Since the signal return will have traveled to and from a fish the effective τ must be double that associated with a particular depth. A number of studies (Cook 1978, Davies 1977) of fish density in schools indicate that for reasonable values for the average extinction cross-section, 2τ can be expected to be considerably larger than unity within some schools.

Some useful scattering approximations depend upon σ_t for the fish being much less or much greater than the acoustical wavelength. Unfortunately these approximations are often not valid. Also many approximations are not valid for pulsed rather than steady-state signals. As a result of these arguments, only a few useful approximations remain. Three were examined which appeared particularly suitable to the present problem: the single scattering approximation, single scattering with attenuation, and the diffusion approximation. The first two are applicable for small τ, while the last is valid for large τ. The solution to the problem for $\tau=1$ is difficult, but may be covered by interpolating the solutions derived from the other approximations.

3.2 Assumptions and general remarks

We make a number of assumptions which will aid in the development of the three approximations above. We assume the transmitted acoustic pulse is short enough to be treated as an impulse but long enough to be treated as narrow-band in frequency so all scattering parameters are computed at a single frequency. We assume enough movement of fish between pings so that the return signals are statistically independent from ping to ping. On the other hand, we assume the numbers density, $\rho(x)$, does not change.

We assume that, although the sonic beamwidth and pulse width are narrow, the density is great enough that many fish are insonified at any instant. This means that we will use integral representations for signal returns rather than discrete forms. We assume all scattering parameters are known or can be approximated. We assume any tendency of the fish to form schools with regular spacing is small enough so that each fish location is an independent random variable.

3.3 Single scattering approximation

This is based upon the simple scattering assumption mentioned at the beginning of this paper. Although the formulation has been well documented, we present a brief derivation as a foundation for later techniques. It will be helpful to refer to Figure 2 for this and later approximations.

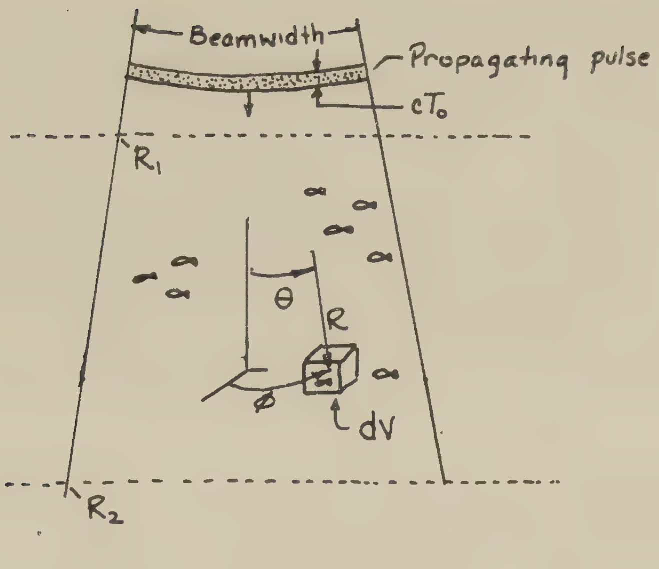

Figure 2. System geometry

Let $P_t(t)$ be the power delivered to the transmitting transducer. [$P_t(t)$ is proportional to the signal envelope.] The received power at the co-located receiver due to backscattering from fish i located at coordinates (R_i,Θ_i,ϕ_i) is

$$P_{r,i}(t) = B^2(\Theta_i,\phi_i)\,\frac{\sigma_{b,i}}{4\Pi R^4}\,P_t\left(t-\frac{2R_i}{c}\right) \tag{10}$$

The function $B^2(\Theta_i,\phi_i)$ includes the two-way beam pattern and transmitting and receiving sensitivities, while c is the sound velocity.

The received power function due to all fish is the sum over all i of the individual returns given by (10). Using the various assumptions given in B above, the summation can be replaced by volume integration employing the numbers density. Thus,

$$P_r(t) = \int_{R_1}^{R_2} \overline{B^2}\,\frac{\overline{\sigma}_b\,\rho(R)}{4\Pi R^4}\,P_t\left(t-\frac{2R}{c}\right)R^2dR \tag{11}$$

where

$$\overline{B^2} = \frac{1}{2\Pi}\int_0^{2\Pi}\int_0^{\Pi} B^2(\Theta,\phi)\sin\Theta d\Theta d\phi \tag{12}$$

and where $\overline{\sigma}_b$ is the backscattering cross-section which is assumed constant over the extent of the school from R_1 to R_2.

If the transmitted pulse P_t is narrow enough so that $\rho(R)/R^2$ can be treated as constant over variations of R equal to $cT_o/2$ where T_o is the pulse width, then Equation (11) reduces to

$$P_r(t) = \frac{A\,\overline{\sigma}_b\,\rho(ct/2)}{(ct/2)^2} \tag{13}$$

The constant A includes $\overline{B^2}$ and a number of other constant terms which drop out of the integration. Equation (13) yields the usual echo integrator formula for the density. Usually the receiver is constructed with a time-varying gain to compensate for the $(ct/2)^2$ spreading effect and other medium losses. A number of references (Maxwell 1980, Ehrenberg 1973, 1978) discuss the effects of error sources upon the density estimate based upon the development above. In general, this approximation is valid so long as 2ι remains much less than unity.

3.4 Single scattering with attenuation

This approximation is a simple extension of the single scattering solution. The basic premise of this approximation is that all energy incident on any fish disappears from the system except for the small amount backscattered to the receiver. Its applications requires knowledge of the average extinction cross-section $\overline{\sigma}_t$ as well as $\overline{\sigma}_b$.

As the incident acoustic wave passes through unit area (normal to propagation direction) and travels a distance dR (the volume traversed is 1·dR) it encounters ρdR scatterers with an average cumulative extinction cross-section of $\overline{\sigma}_t \rho dR$. This is the fraction of the incident energy that is removed. Thus, if I(R) is the incident intensity at depth R, then

$$\frac{dI(R)}{dR} = - \overline{\sigma}_t \rho(R) I(R) \tag{14}$$

Consequently

$$I(R) = I_0 \exp\{-\int_{R_0}^{R} \overline{\sigma}_t \rho(R) dR\} = I_0 e^{-\tau(R)} \tag{15}$$

Now this attenuated intensity can be used in place of the unattenuated power in Equation (11). Doing so yields the following expression for the received power

$$P_r(t) = \int_{t_1}^{t_2} \overline{B^2} \frac{\overline{\sigma}_b}{4\Pi} \frac{\rho(ct'/2)}{(ct'/2)^2} P(t-t') \exp\{-2\int_{t_1}^{t'} \rho(c\xi/2) \overline{\sigma}_t \frac{c}{2} d\xi\} \frac{c}{2} dt' \tag{16}$$

The factor of 2 in the exponent is due to the two-way attenuation.

If the school is far away relative to a pulse length, then as long as τ remains small ($\tau < .2$, say) then an estimate for the density in the i^{th} time interval can be found based on the estimates of $\hat{\rho}$ from the previous i-1 intervals

$$\hat{\rho}_i = \frac{E_r(\Delta t_i)}{\Delta t_i} \exp\{\sum_{j=1}^{i-1} \hat{\rho}_j \overline{\sigma}_t \, c \Delta t_j\} \tag{17}$$

where

$$E_r(\Delta t_i) = \int_{t_{i-1}}^{t_i} G(t) P_r(t) dt, \qquad \Delta t_i = t_i - t_{i-1} \tag{18}$$

The factor G(t) includes the time-varying gain, backscattering cross-section $\overline{\sigma}_b$ and other constants. The positive exponential factor in (17) simply compensates for the attenuation affecting each depth. A discussion of the errors of this approximation is discussed in Maxwell (1980) and in a following section.

3.5 The diffusion approximation

While the previous approximations are valid only for tenuously-distributed fish populations, the diffusion approximator is generally valid only for dense schools, or when τ becomes somewhat greater than unity. The diffusion approximation assumes that the acoustic intensity at any point in the volume is comprised only of intensities which have been already scattered at least once. Further, the approximation is valid only when the spatial distribution of the intensity is nearly isotropic. For this to be the case, the number of scatterers which the acoustic pulse must have already encountered depends on the asymmetry factor $\overline{\mu}$. For small $\overline{\mu}$, for example, the fish size-to-wavelength ratio is small and only a few scatters are necessary for scattered intensity to be considered nearly isotropic. The diffusion solution for $\sigma_{b/A}(t)$ starts at t=0 which is defined as the time at which the incident pulse first hits the top of the layer of scatterers. The solution is only valid after a time, T_d, sufficient to allow a large enough number of intercepts of the incident pulse with scatterers. For the rest of this paper the theoretical value of this lower time limit for validity will be

$$T_d \triangleq \sqrt{3}\ (\rho c[\bar{\sigma}_s(1-\bar{\mu}) + \bar{\sigma}_a])^{-1} \qquad (19)$$

The derivation of the diffusion solution is beyond the scope of this paper (see Ishimaru 1978). However, some restrictions and assumptions necessary for the derivation should be noted. Density variations within the school are difficult to handle so it is assumed that the school, existing from R_1 to R_2 has constant density ρ. (The results can be extended to schools whose density varies slowly with R.) The effect of geometric spreading is eliminated by assuming $R_1 >> R_2 - R_1$.

Let us define a time-varying quantity called the backscattering cross-section per unit area, $\sigma_{b/A}(t)$. This quantity, independent of transducer and propagation parameters, represents the intensity emerging from a unit area on the upper surface of the school at time t, directed toward the receiver (see Figure 3). This response is assumed to be relative to a 1 joule/m^2 plane pulse incident on the layer of fish.

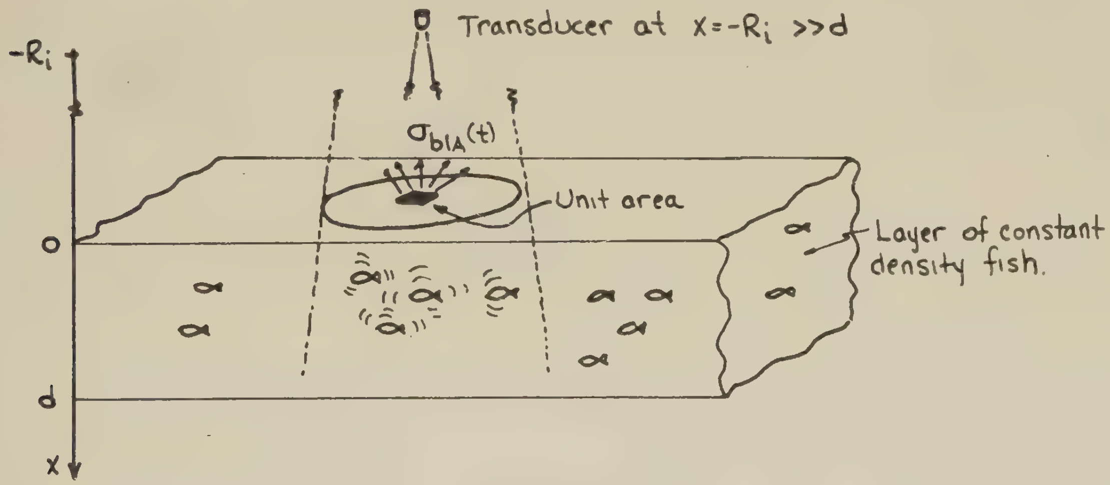

Figure 3. Illustrating the effective radiation from the top surface of the school.

Some examples of the diffusion solution are shown in Figures 4 and 5. These illustrate the effects of density, school extent, assymetry factor and relative absorption characteristics (σ_a/σ_t) on the predicted response $\sigma_{b/A}(t)$. The lower limits of validity are shown, as well. For $t > T_d$, the response resembles a decaying exponential whose time constant is

$$t_c = (\rho c(\sigma_a[\sigma_t - \bar{\mu}\sigma_s])^{1/2})^{-1}, \qquad t > T_d \qquad (20)$$

This should be compared to the single scattering with attenuation time constant

$$t_A = (\rho c \sigma_t)^{-1}, \qquad t \geq 0 \qquad (21)$$

and the single scattering time constant

$$t_{ss} = \infty, \qquad t \geq 0 \qquad (22)$$

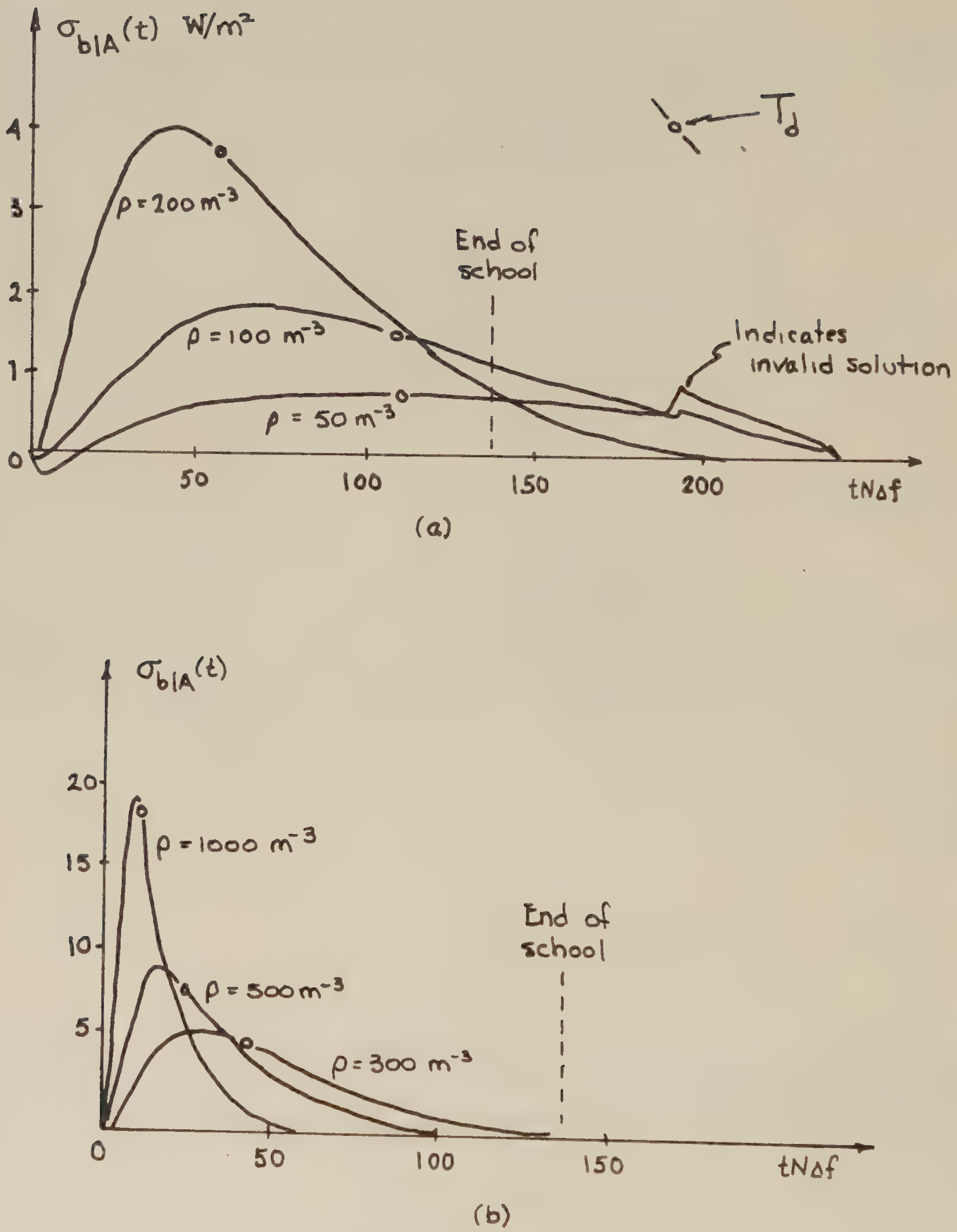

Figure 4. Diffusion solutions for different densities with: $\sigma_s = 7.5$ cm², $\sigma_a = 2.5$ cm², $d = 20$ m, $\overline{\mu} = .6$, $N\Delta f = 5120$.

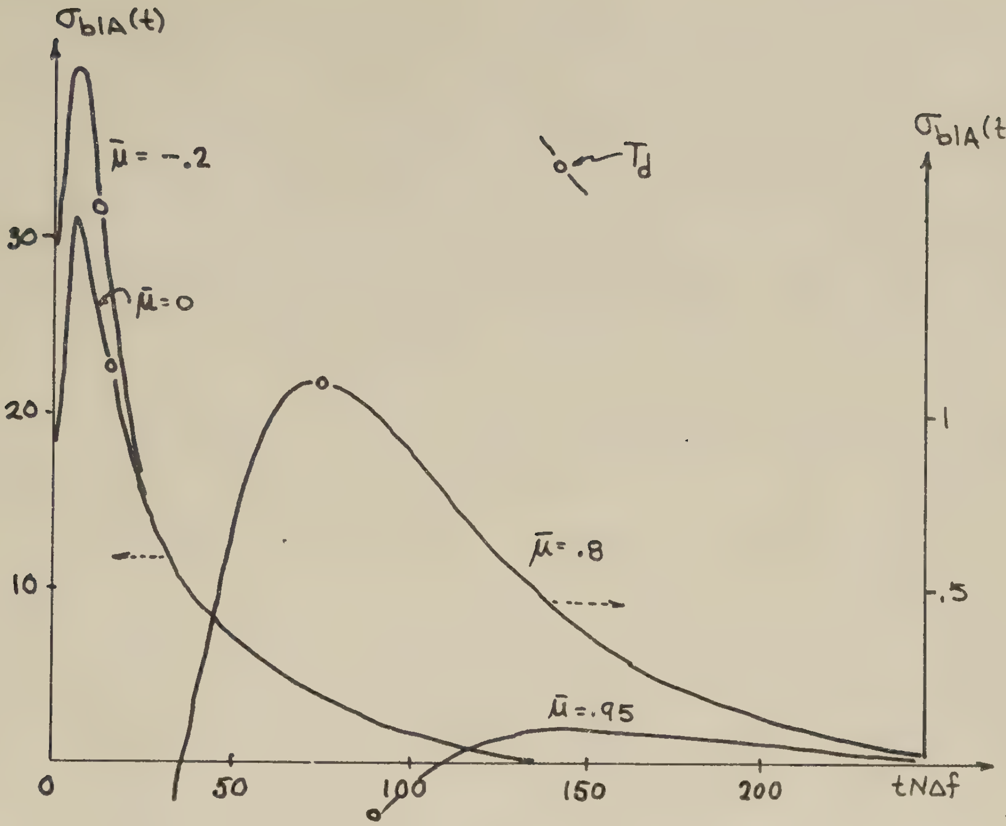

Figure 5. Diffusion solutions for various $\bar{\mu}$ with:
$\rho = 200\ \text{m}^{-3}$, $\sigma_s = 7.5\ \text{cm}^2$, $\sigma_a = 2.5\ \text{cm}^2$, $d = 40$ m, $N\Delta f = 4096$.

The diffusion solution itself is valid only if the school extent d is such that $T_d < d/c$.

For dense or extensive fish populations, especially those which contain absorptive or or isotropically scattering fish at the frequency of insonification, much of the received power is expected to be due to diffusion phenomena. Note that a distinctive feature of diffusion solutions is that there is no end of the school easily identifiable from the echo. Absorption and multiple scattering are responsible for the observed phenomena reported in Lytle and Maxwell (1978) and Bakke and Bjorke (1973) including elongated echoes relative to the school extent, and displaced or absent returns from the sea floor or objects lying beyond the school. A more comprehensive treatment of the diffusion solution, its inherent problems, and error sources is contained in Maxwell (1980).

3.5 Echo prediction

The impulse response functions $\sigma_{b/A}(t)$ can be easily compared for each of the approximations discussed earlier, for constant density fish schools. For a school of thickness d, the single scattering approximation predicts

$$\sigma_{b/A}(t)_{ss} = \frac{\rho\sigma_b c}{2} \qquad 0 \le t \le 2d/c \tag{23}$$

while the single scattering with attenuation model gives

$$\sigma_{b/A}(t)_A = \frac{\rho\bar{\sigma}_b c}{2}\exp[-\rho c\bar{\sigma}_e t]\ , \qquad 0 \le t \le 2\frac{d}{c} \tag{24}$$

The two functions above depend upon the parameters $\bar{\sigma}_b$ and $\bar{\sigma}_t$ while the diffusion solution depends upon σ_s, σ_a, and $\bar{\mu}$. Thus in order to relate or combine the different solutions theoretically we must assume or measure the relationships between these various parameters. We will examine a number of cases where this can be done.

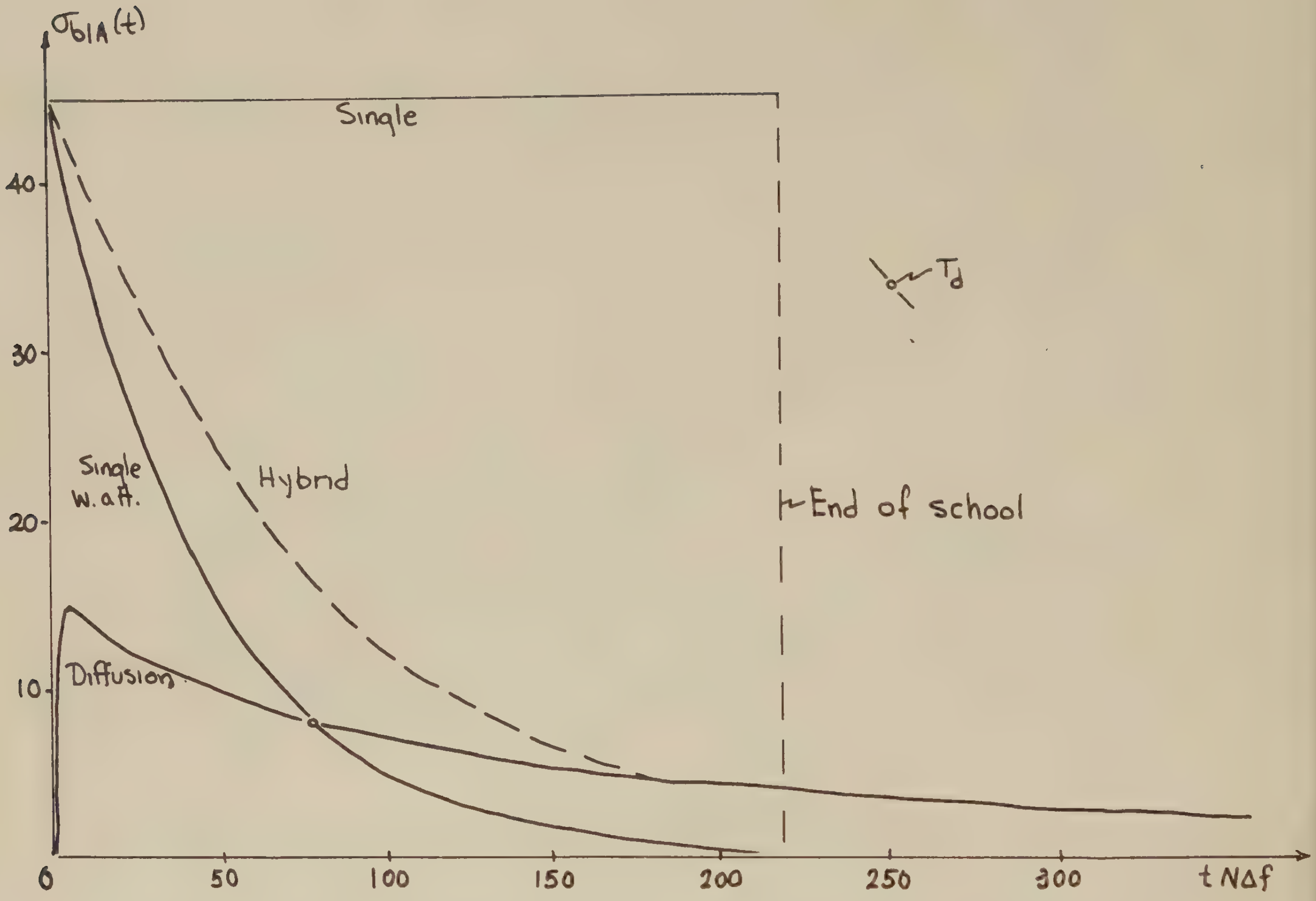

Figure 6. Comparison of model solutions for isotropically scattering fish with: $\rho = 120\ m^{-3}$, $\sigma_s = 5\ cm^2$, $\sigma_a = .1\ cm^2$, $\bar{\mu} = 0$. Total energy return for unit energy transmitted: single = 2.4, single with attenuation = .49, hybrid = .92.

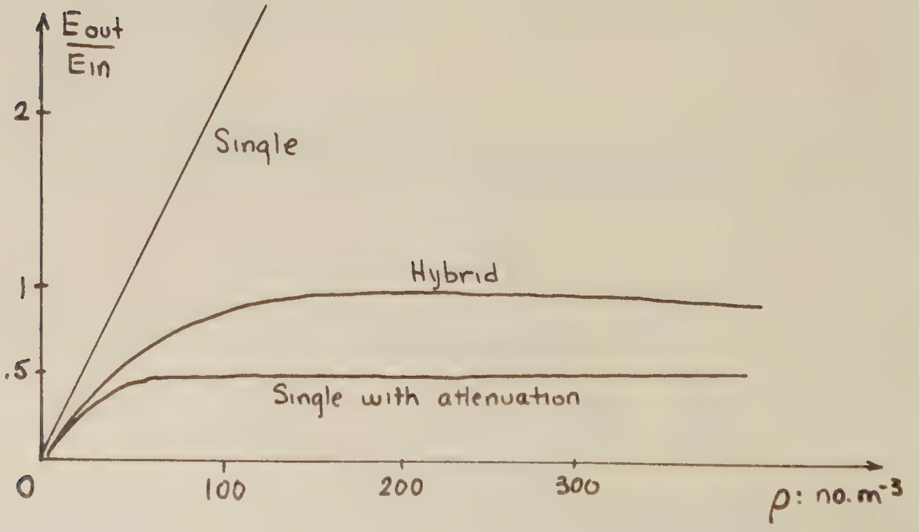

Figure 7: Output to input energy comparisons for various scattering models with: $d = 40\ m$, $\sigma_s = 5\ cm^2$, $\sigma_a = .5\ cm^2$, $\bar{\mu} = 0$.

Consider the case where the fish can be considered to scatter isotropically, $\overline{\mu} = 0$. (This would be approximately the case for 15 cm fish at frequencies below 10 kHz.) In this case, $\sigma_s + \sigma_a = \overline{\sigma}_t$ and $\overline{\sigma}_s = \overline{\sigma}_b$. Figure 6 shows the three solutions for the indicated parameter values as well as hybrid of the solutions. The single scattering solution is proportional to the density throughout the school. Note that under this assumption a greater returned energy/area is predicted than is incident, which arises from the approximation's violation of energy conservation. The single scattering with attenuation solution in this example disappears before $t = 2d/c$. The former solution overestimates the response by assuming no attenuation due to scattering and absorption. The latter solution underestimates the response by assuming that no scattered energy (other than that directly backscattered) follows a path to the receiver. The true solution, then, is expected to lie somewhere between the two tenuous-media approximations.

The "hybrid" solution shown in Figure 6 is one possible response. For $t > T_d$, the true response can reasonably be determined by adding the diffuse and attenuated incident intensities (scattered plus direct wave responses). For $t \leq T_d$, we can argue that the reflected energy per unit area should be nearly given by

$$\text{Reflected Energy} \approx (\text{Incident} - \text{Transmitted} - \text{Absorbed})\ \text{Energy} \qquad (25)$$

The energies absorbed and transmitted due to the attenuated incident energy can be easily approximated, but those due to diffusion cannot. The reflected energy/area estimated by ignoring the latter will therefore be greater than the actual reflected energy/area. The hybrid solution shown is an exponential fit determined from estimated a reflected energy/area and the value of the response at $t = T_d$. Figure 7 shows a comparison of relative returned energy versus density for the three complete response predictions, using the parameters of Figure 6. Total reflected energy does not appear to be a good quality on which to base a density estimate.

Figure 8 shows the response for the same theoretical fish school at a frequency which makes them resonant scatterers. For isotropically-scattering, absorbing fish, virtually no energy may be returned from the most distant fish.

For large fish (compared to the wavelength), $\overline{\mu} \rightarrow 1$. The average backscattering quantity $\overline{\sigma}_b$ is then on the order of $\sigma_s/2$. If $\overline{\sigma}_b = \sigma_s/2$, the response would be as shown in Figure 9 for fairly high absorbing fish. For the general case, however, there is no method of accurately relating the beamwidth-averaged quantities $\overline{\sigma}_b$ and $\overline{\sigma}_t$ to the diffusion parameters σ_s, σ_a, and $\overline{\mu}$ without measurement. Our measurements, for example, indicate that $\overline{\sigma}_b$ is two to four times larger than $(\sigma_t - \hat{\sigma}_a)/2$, where $\hat{\sigma}_a \approx 2\ \text{cm}^2$. The character of the predicted hybrid response, primarily the time constant associated with the exponential fit, depends on this relationship and a priori knowledge of all five scattering parameters.

So what can be said about the echo returned from a constant-density fish school? The predicted response can be approximated by a function

$$\sigma_{b/A}(t) = \frac{\rho\overline{\sigma}_b c}{2} \exp[-\gamma(t)t] \qquad (26)$$

The time-varying quantity $\gamma(t)$ depends on the absorption, scattering, and diffusion characteristics of the scatterers. It is related to the anticipated angular distribution of the intensity within the scattering volumes. Under the tenuous media approximations, $\gamma(t)$ is constant and equal to the inverse of the time constant given by Equations (21) and (22). The hybrid predicted responses are

$$\gamma(t) = \begin{cases} \rho c(k\sigma_s + \sigma_a) \text{ for } 0 \leq t \leq T_d \\ \rho c[\sigma_a(\sigma_t - \overline{\mu}\sigma_s)]^{1/2} \text{ for } t \geq T_d \end{cases} \qquad (27)$$

where k is approximately 0.6 for isotropic scatterers, and 1.18 for large spherical scatterers (or for $\overline{\sigma}_b \approx \sigma_s/2$). Note that using $\sigma_s = 0$ would correspond to an absorption-only intensity loss. A value $k = 0$ would correspond to a best-guess, conservative hybrid response for $\overline{\sigma}_b$ related to σ_s in an unknown manner. All of these options will be categorized by accuracy and risk in applying them to density estimation.

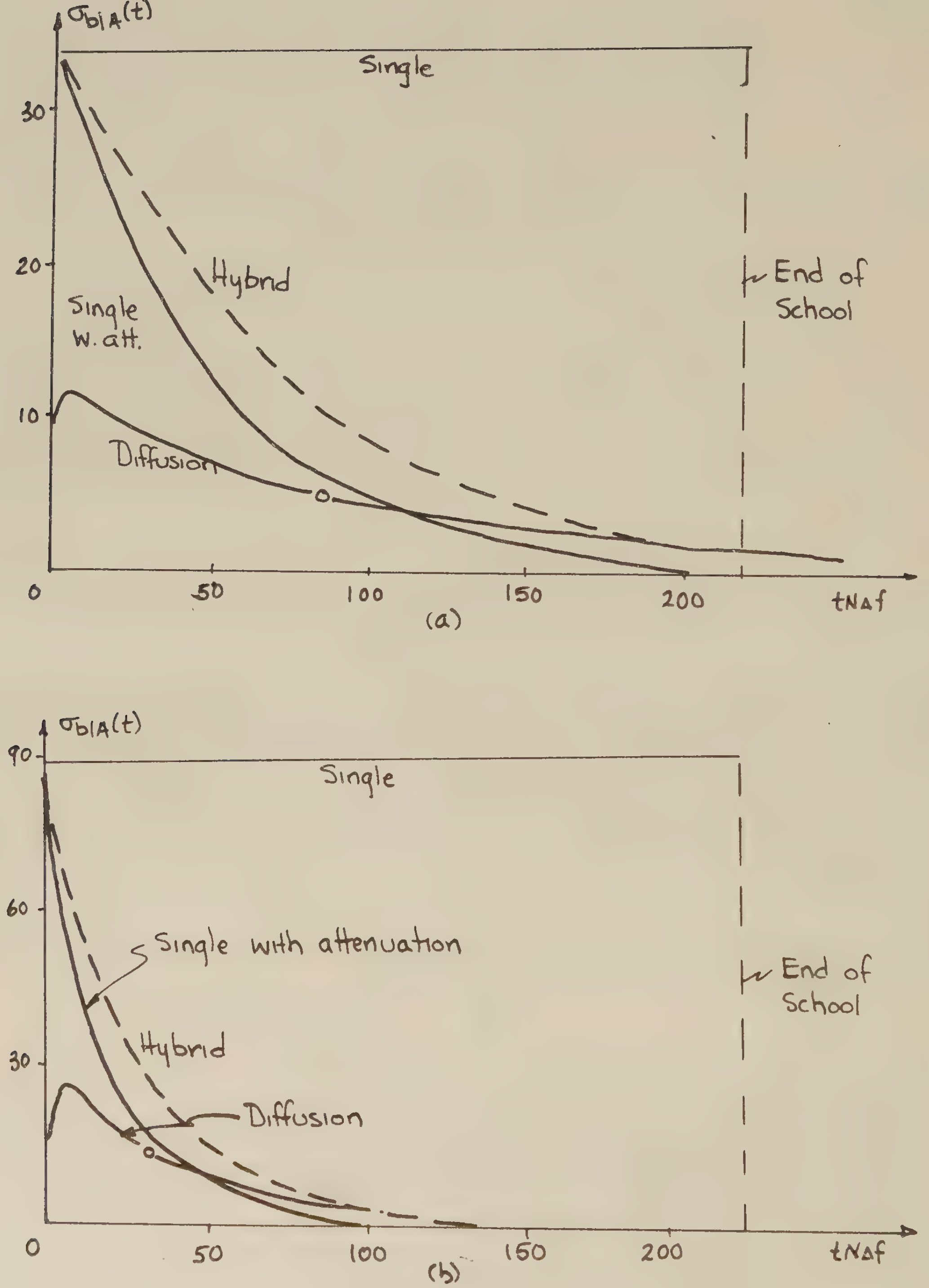

Figure 8: Impulse response predictions for resonant fish with: $\sigma_s = 15\ cm^2$, $\sigma_a = 4\ cm^2$, $\overline{\mu} = 0$, $d = 40\ m$, $N\Delta f = 4096$, and (a) $\rho = 30\ cm^{-3}$, (b) $\rho = 80\ cm^{-3}$.

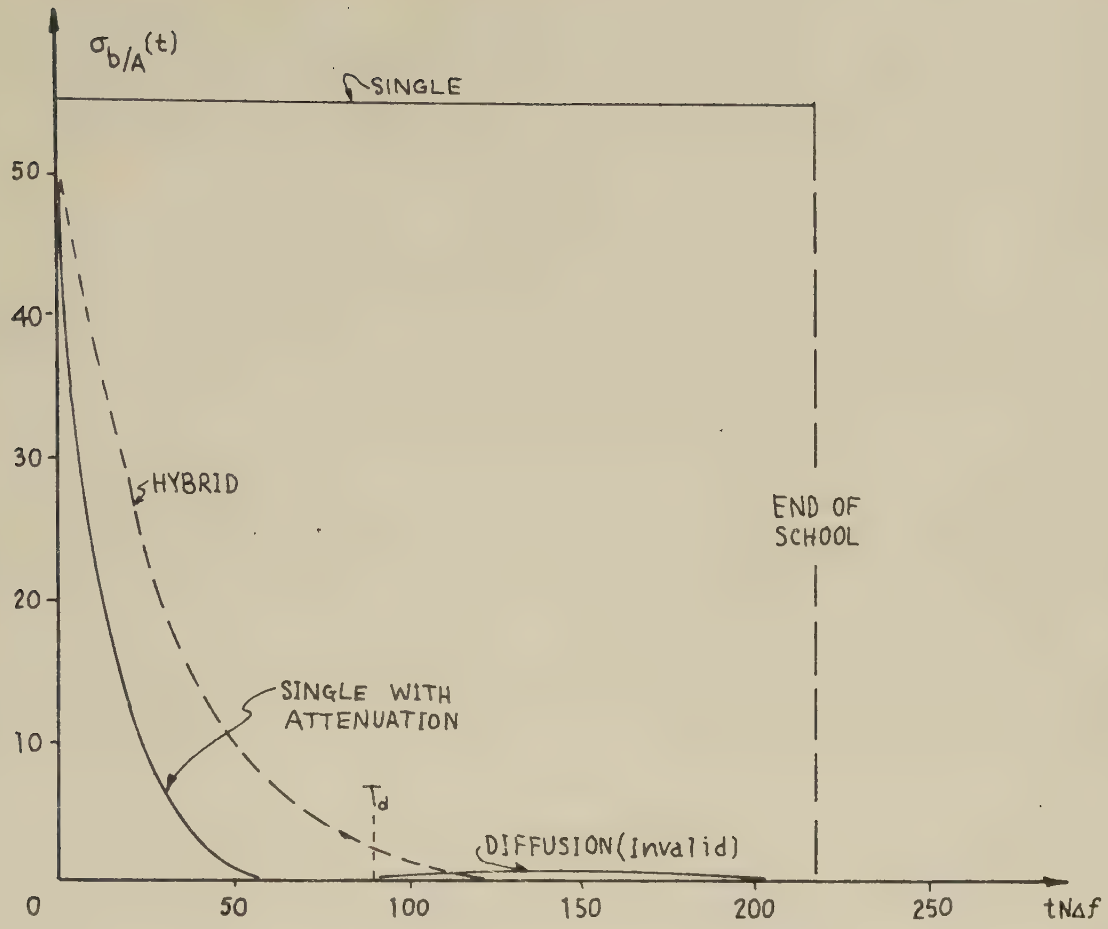

Figure 9: Impulse response for large ($L/\lambda >> 1$), absorbing fish with: $\rho = 200\ m^{-3}$, $\sigma_s = 7.5\ cm^2$, $\sigma_a = 2.5\ cm^2$, $\overline{\mu} = .95$, $N\Delta f = 4096$.

4. DENSITY ESTIMATION

4.1 Echo processing

The structure of the proposed density estimation technique is essentially the same as that already discussed for single scattering with attenuation. The return echo power is integrated over time intervals and then multiplied by a gain factor, $\exp\{\gamma(t)t\}$, where $\gamma(t)$ is computed from density estimates of the preceding intervals.

4.2 Scattering parameters

Regardless of the scattering approximation(s) used for estimating fish density, the received power is always related to products of density and scattering cross-sections. The density cannot be accurately estimated without sufficient knowledge of the required scattering parameters. Methods exist for in situ estimation of $\overline{\sigma}_b$ (Ehrenberg, 1978). Other cross-sections must be obtained from measurement or modelling, as discussed in preceding sections.

After $\overline{\sigma}_b$ the next most important scattering value to know is the dorsal beamwidth-averaged extinction cross-section $\overline{\sigma}_t$. This parameter is required to measure optical density τ, which in turn indicates the extent of multiple scattering and absorption. It is thus used to provide a measure of confidence in the estimate obtained from the simple echo integrator. Two additional parameters (easily estimated) can be used to provide low-risk density estimation improvements: the absorption cross-section σ_a and the scattering cross-section for fish small relative to a wavelength, σ_s.

TABLE I

Summary of Approximations and Gains

Scattering Approximation	Conditions for Best Use	$\gamma(t)$ [Gain = $e^{\gamma(t)t}$]	Comments on Accuracy in Dense Environment
Single	$2\tau_N \lesssim .2$	0	No Risk, Poor Accuracy
Single With Attenuation	$2\tau_N \lesssim .2$	$\rho c \Delta t\ \sigma_t$	High Risk, Poor Accuracy
Single With Absorption	$2\tau_N \lesssim .2$	$\rho c \Delta t\ \sigma_a$	No Risk, Fair Accuracy
Lossless Isotropical Scatterers	$\frac{\sigma_a}{\sigma_s} << 1,\ \overline{\mu} = 0$ $(L/\lambda < 1)$	$\rho\ \Delta\ \frac{\sigma_s}{\sqrt{3}}$ (1)	Small Risk, Fair Accuracy
Lossy Isotropic Scatterers	Resonant Scatterers $(\sigma_a/\sigma_s) \gtrsim .1$	$\rho c \Delta t(\frac{\sigma_s}{\sqrt{3}} + \sigma_a)$ (1)	Medium Risk, Medium Accuracy
Large Fish, $\sigma_b \simeq \sigma_\delta/2$	$(\frac{L}{\lambda} >> 1)\ :\overline{\mu} \rightarrow 1$	$\rho c \Delta t(\frac{\sigma_s}{3.4} + \sigma_a)$	?
Large Fish $\sigma_b \neq \sigma_\delta/2$	$(\frac{L}{\lambda} >> 1)\ ;\overline{\mu} \rightarrow 1$	$\rho c \Delta t \overline{\sigma}_b < \gamma(t) <$ $\rho c \Delta t(\frac{\sigma_s}{3.4} + \sigma_a)$ (1)	?
Diffusion Only	$t \gtrsim T_d : 2\tau_N >> 1$	$\rho c \Delta t(\sigma_a \sigma_{tr})^{1/2}$ (2)	Moderate Risk, Good Accuracy

(1) Use Diffusion gain for $t \gtrsim T_d$.

(2) $\sigma_{tr} = \sigma_s(1-\overline{\mu}) + \sigma_a$

4.3 Implementation

Fish school density estimates are usually obtained as a function of depth (range) by dividing the response into N range intervals of length $c\Delta t_i$. The density within an interval is assumed to be nearly constant. The estimate for cell i is then given by

$$\hat{\rho}_i = \frac{2\hat{\sigma}_{b/A}(\Delta t_i)}{\overline{\sigma}_b c} \tag{28}$$

This estimate gives a lower bound on the density. The error in the estimate (due to the single scattering assumption, only) for interval i is less than 10 per cent as long as

$$2\hat{\tau}_i = \sum_{j=1}^{i-1} \hat{\rho}_j \overline{\sigma}_t \; c \; \Delta t_j < .2 \tag{29}$$

The total biomass estimate error will be less than 10 percent if $2\hat{\tau}_N \leq .2$. On the other hand, the maximum error created by the use of Equation (16) as an estimator is approximately the same, for exactly known $\overline{\sigma}_t$. This latter estimator provides an upper bound on the density.

In addition to the tracking of $2\hat{\tau}_i$ throughout the school, other observations, if available, can indicate the extent of higher-order scattering. For example, if the seafloor echo is weak, displaced, or missing, or if the school response is elongated or clearly exponential in form, it may be assumed that Equation (28) will not provide a good biomass estimate.

Table I is a compilation of factors including assessment of risks and expected accuracy. It should be noted that one difficulty encountered in implementation is the determination of gain cutoff (end of school). This is important whenever diffusion or absorption is extensive. If the estimated value T_d is exceeded early in the response, the cutoff point may be taken as approximately (response end)/$\sqrt{3}$. Otherwise, an independent determination of school thickness or empirical estimation from response predictions (or experience) is required. From the conservative estimator viewpoint, it is better to cut off the gain too early than too late.

5. CONCLUSIONS

Most of the sources of error involving the echo integrator density estimation technique have received considerable attention. An exception has been the error due to scattering assumptions upon which the method is based. The use of optical density estimation as described above is recommended as a tool for at least qualitatively determining this error. Whenever this quantity approaches unity, the biomass estimate may be in error by an unacceptable amount. The measurements shown for $\overline{\sigma}_t$ in this discussion, for 15 cm trout at 241 kHz, are not obviously extendable to other frequencies or sizes and species of fish. The method outlined in Section 2 provides a means of determining this valuable parameter. Given that the decision is made to improve the estimation accuracy, the procedure presented herein offers this opportunity. It is especially useful for small, resonant, or absorbing scatterers in a dense or extensive population.

ACKNOWLEDGEMENT

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COMPTAGE DES ECHO - TRACES ET INTEGRATION DES SIGNAUX, DEUX METHODES ACOUSTIQUES APPLIQUEES A L'EVALUATION DE LA BIOMASSE DU STOCK DE HARENGS DE STRAIT OF GEORGIA (ETAT DE WASHINGTON, E.U.)

par

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ABSTRACT

Counting the fish on a echogram seems a method somewhat archaic in comparison to echointegration. However, it may be shown to be as precise as integration, and much less expensive, when the fish are scattered enough and the area to be covered is not too large.

We had the opportunity to compare the two methods, admittedly in a nearly ideal case: a quasi mono-specific population of fish with a small size range and different degrees of concentration but not schooling. This population of herring enters the Georgia Straits (Wa, USA) for a few months and is assessed by the Department of Fisheries by means of regular one-night acoustic cruises when ten transects are covered.

The sampled volume had been derived initially from the directivity pattern of the transducer. A good correlation was found between densities calculated by counting and by echo-integration (data were presented by 5 metre layers) but with a considerable systematic error. The way used to evaluate the volume was suspect and an other method has been tried: the real sampling volume ie corresponding to the echogram, was determined from the integrator data for each layer.

Then those volumes have been used to calculate the fish density by counting for three other cruises. There was a very good correlation between them and densities from echo-integration.

The following conclusions can be made:

There is a very good proportionality between densities evaluated by echointegration and counting, at least in the case where the fish are scattered and the population is homogeneous;

The sampling volume corresponding to the echogram strongly depends on the gain and threshold of the recorder as well as the sensivity of the paper. Its determination is not evident;

An alternative is to "calibrate" the system using known fish densities for different ranges (mainly by echointegration);

Hence it is possible to use this calibrated echosounder for quantitative evaluation by counting, providing the overall conditions to not change much.

RESUME

Compter les poissons sur un enregistrement papier de sondeur peut paraître une méthode quelque peu archaïque par rapport à l'écho-intégration. Cependant elle peut se révéler aussi précise que l'intégration, et beaucoup moins onéreuse, si les poissons sont bien dispersés et la zone à étudier pas trop grande.

L'occasion de comparer les deux méthodes nous a été fournie dans un cas presque idéal: il s'agissait d'une concentration de poissons quasi monospécifique et de taille homogène, présentant différents degrés d'agrégation sans aller jusqu'au banc véritable. Cette population de hareng pénètre dans le détroit de Georgie (Etat de Washington, E.U.) où elle demeure quelques mois. Elle est étudiée par le Département des Pêches

qui suit régulièrement son évolution par des campagnes acoustiques d'une nuit comprenant chacune dix radiales.

Le volume échantillonné par le sondeur a été tout d'aboard déduit du diagramme de directivité du transducteur. Les densités évaluées par comptage et par écho-intégration (les données étaient présentées par couche de 5 m) étaient bien corrélées, mais avec une erreur systématique considérable. On suppose que celle-ci provenait d'une mauvaise évaluation du volume de détection. On a alors déterminé le volume réellement échantillonné dans chaque tranche en comparant comptage et écho-intégration. Ces volumes ont ensuite été utilisés pour calculer la densité en poissons par comptage pour trois autres campagnes. On a trouvé une très bonne corrélation entre ces densités et celles évaluées par écho-intégration.

1. METHODOLOGIE

L'évaluation de la densité, relative ou absolue, en poissons par comptage des écho-traces a été pratiquée assez largement par le passé (par example, Cushing, 1968; Midttun et Saetersdal, 1957). L'avènement de l'écho-intégration et son développement au cours de la dernière décennie a quelque peu fait tomber cette technique en désuétude bien qu'elle lui ait été reconnue théoriquement supérieure dans le cas de détections séparées (Ehrenberg, 1977). Il faut bien reconnaître que l'utilisation du comptage des échos comme méthode quantitative se heurte notamment au problème de la détermination rigoureuse du volume réel échantillonné. Dans les cas où on a affaire à une population homogène et à une densité de répartition relativement faible il peut être justifié d'utiliser cette méthode nécessitant moins de moyens que l'écho-intégration tout en étant également fiable.

Les résultats que nous présentons ci-dessous ont été obtenus sur une population de hareng (Clupea harengus pallasi) qui pénètre dans le "Strait of Georgia" au cours d'une migration de reproduction et y demeure environ trois mois, d'avril à juin. Elle est alors l'objet d'une pêche commerciale assez intensive. Sa surveillance est réalisée notamment par des campagnes acoustiques répétées et des pêches expérimentales organisées par le Department of Fisheries de l'Etat de Washington. Au cours de sorties, qui durent chacune une nuit, toute la zone de concentration de cette population est couverte par un réseau de 10 radiales. L'information acoustique est enregistrée sur bande magnétique analogique, puis traitée à l'Université à l'aide d'un calculateur DIGITAL PDP 11 (un système semblable est décrit dans Thorne, 1977). Les résultats sont présentés sous forme de densités exprimées en kg par mètre cube moyennées par intervalle de profondeur (5 ou 10 mètres) et par radiale. Chaque radiale est représentative d'un secteur dont la biomasse est calculée par multiplication de la densité moyenne par unité de surface par la superficie. Cette description, ainsi que ce qui suit, se réfère au printemps 1978.

Les caractéristiques principales de l'appareillage utilisé et les conditions d'emploi sont:

Sondeur Ross 105 kHz, transducteur type 265 d'ouverture nominale 7^o5. Fréquence de récurrence, 2 émissions par seconde. Durée de l'émission, 0,6 ms. Fonction GVT, 20 log R + 2α R. Vitesse de croisière, 9,5 noeuds soit environ 5 m/s.

L'enregistrement graphique des détections (enregistreur ROSS "Fineline") est excellent et présente notamment une grande finesse de trait. Ceci nous a incité à faire une étude comparative entre les densités évaluées par écho-intégration et par comptage sur papier.

2. CALCUL DU VOLUME DE DETECTION

L'examen de l'enregistrement sur papier de la sortie n^o 8 à laquelle nous avons participé nous a permis de constater:

- qu'il n'y avait pas de recouvrement décelable aux profondeurs de détection
- que la densité ne paraissait pas atteindre le niveau des échos multiples, tout au moins de facon importante.

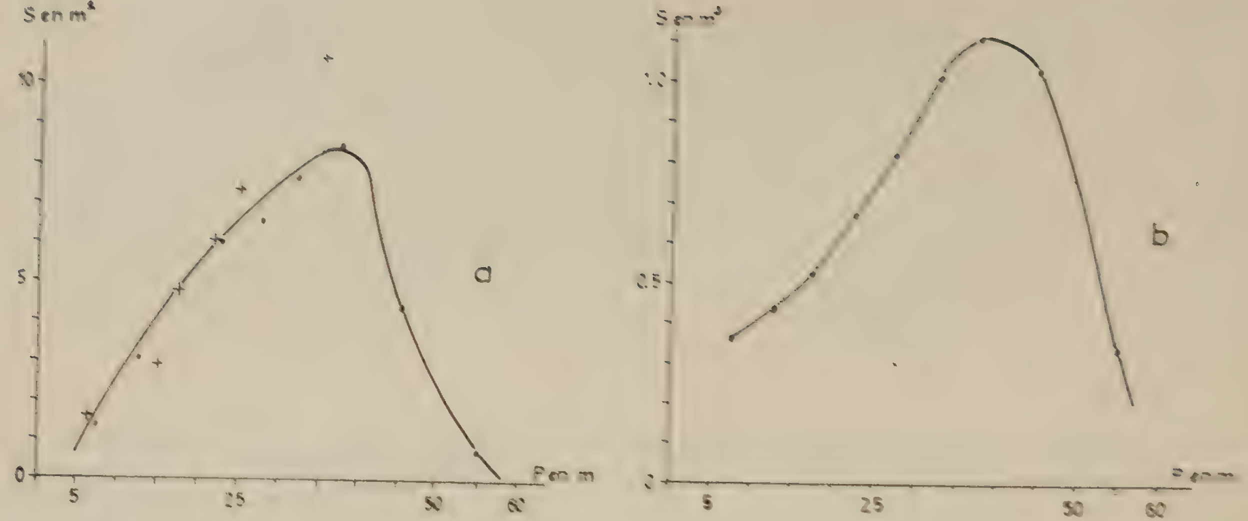

Fig. 1. Section S du faisceau acoustique en fonction de la profondeur P. a: estimée à partir du diagramme de directivité et de la portée (•), et à partir de comptages à l'oscilloscope (+) adapté de N. Lemberg. b: calculée par comparaison entre comptage et écho-intégration.
Cross section S of the beam versus depth P. a: from directivity pattern and maximum range (•), and from direct counting with oscilloscope (+) adapted from N. Lemberg. b: from comparison between counting and integration.

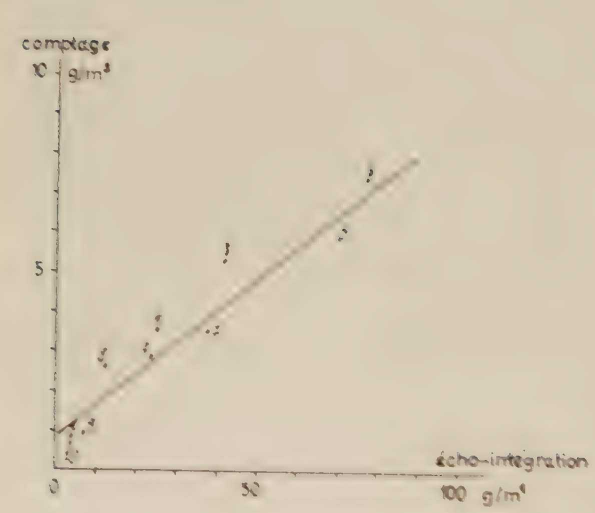

Fig. 2. Densités en poissons évaluées par écho-intégration et par comptage en utilisant le volume de détection probable, sortie n° 8, moyennes par radiale (les numéros correspondent aux radiales).
Fish density determined by echo-integration and by counting, using the estimated sampling volume, from cruise 8, data points represent the average value of each transect 1 to 10.

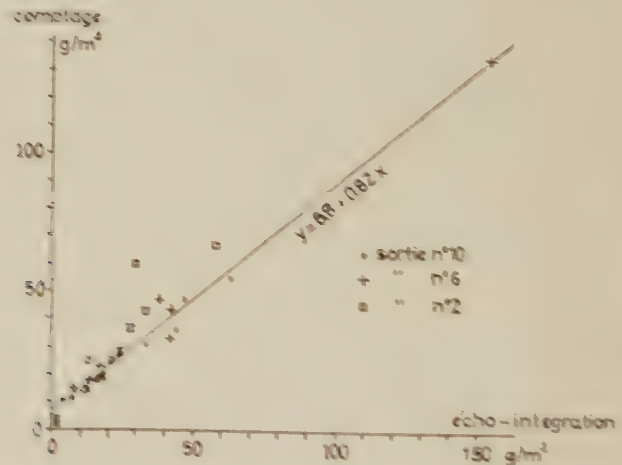

Fig. 3. Densités par écho-intégration et par comptage en utilisant le volume de détection correspondant à l'enregistrement graphique (moyennes par radiale). La droite et l'équation correspondent aux sorties 6 et 10, voir texte.
Fish density from echo-integration and counting, using the sampling volume corresponding to the graphical record, data points represent the average value of each transect. The regression line and the equation both correspond to cruises 6 and 10, see text.

Ces deux constations nous ont amené à admettre que chaque émission pouvait être considérée comme indépendante, tout au moins en ce qui concerne l'enregistrement graphique. Ainsi le volume détecté (volume de confusion) correspondant à cet enregistrement peut être exprimé par:

$V = R^2 \; \Delta R \Omega$

avec R = profondeur de la détection

ΔR = hauteur de l'intervalle de détection

Ω = angle solide correspondant à la, directivité du transducteur et au seuil de détection du poisson.

Le calcul de ce volume à partir du diagramme de directivité était compliqué par le fait que l'on avait utilisé la fonction 20 log R + 2 α R. Cependant aucune détection n'apparaissant au-delà de 60 m; on a considéré que les seules cibles détectées à 60 m se trouvaient sur l'axe acoustique (limite de portée) et qu'elles avaient le même index de réflexion moyen TS que celles se trouvant à d'autres profondeurs. A la différence entre la perte de propagation non compensée en limite de portée R_{max} et la perte à la profondeur intermédiaire R correspondra l'angle de détection d'après le diagramme de directivité émission-réception.

$20 \log R_{max} - 20 \log R = a\text{dB}$

$\frac{a}{2} \text{ dB} \rightarrow \theta^o_{(R)}$

$\theta^o_{(R)}$ est lu sur le diagramme de directivité

A partir de la profondeur 5 m et pour chaque strate de profondeur, on a calculé la section du faisceau acoustique. Celle-ci est portée sur la Fig. 1a.

Les angles de détection et les sections correspondantes ont également été déterminées pour un certain nombre de profondeur par observation à l'oscilloscope du nombre de fois qu'un poisson était détecté à une vitesse connue. Ces observations ont été faites par N. Lemberg du Department of Fisheries qui nous les a aimablement communiquées. Elles portaient sur des harengs matures comparables en taille à ceux qui font l'objet de la présente étude. Ces valeurs sont également portées sur la Fig. 1a.

On remarquera que jusqu'à la profondeur de 25 m environ les valeurs se superposent bien, la dernière mesure à l'oscilloscope dépassant assez fortement la valeur calculée: ceci peut très bien provenir du fait que la portée maximum dépasse largement 60 m mais qu'il n'y avait pas de poissons à cette profondeur.

Néanmoins, les deux séries de valeurs concordent suffisamment pour considérer la courbe comme représentative et l'utiliser dans le calcul des densités, la majorité des détections se situant dans les couches supérieures à 35 m.

La densité en nombre (d) a été calculée en divisant le nombre de poisssons (Nf) comptés dans chaque strate de profondeur par le nombre d'émissions (p), la hauteur de la strate (ΔR) et la section correspondante (S) en m^2.

$$d = N_f \cdot \frac{1}{p} \cdot \frac{1}{\Delta R} \cdot \frac{1}{S}$$

La densité en poids (ρ) est obtenue en multipliant le résultat par le poids moyen d'un poisson, $\bar{w}$:

Ici $\bar{w}$ = 120 g. $\qquad \rho \text{g/m}^2 = d. \bar{w}$

Les densités moyennes par radiale (ρc) ont été calculées et comparées aux densités évaluées par écho-intégration (ρ_1). Ces données d'ajustent bien à une droite (fig. 2), mais dont la pente est très éloignée de 45^o.

$\rho c = 0,86 + 0,08\ \rho i \qquad r = 0,96$

On voit qu'il existe un facteur proche de 10 entre ces deux estimations. Si l'on tient pour justes les densités évaluées par écho-intégration (elles correspondent à de multiples observations et sont concordantes avec d'autres sources d'information), il faut admettre que le calcul du volume de détection est erroné : du reste ceci est confirmé par le non-recouvrement des émissions successives qui interviendrait à partir de 20 m dans l'hypothèse précédente. En fait le gain et le seuil de l'enregistreur doivent réduire considérablement la dynamique du système, et partant le volume apparent de détection.

On a alors utilisé les densités évaluées par écho-intégration pour calculer les volumes (ou sections) de détection pour chaque strate. Considérant chaque émission isolèment, ce volume moyen V peut s'écrire :

$$V = N_f \cdot \bar{w} \cdot \frac{1}{p} \cdot \frac{1}{\rho i}$$

La section moyenne du volume apparent de détection sera approximativement égale à :

$$S = \frac{V}{D}$$

ou D = hauteur de la strate

TABLEAU 1: Section du faisceau acoustique calculée d'après la comparaison comptage-écho-intégration. Les radiales 1 et 10 ainsi que valeurs entre parenthèses n'ont pas été retenues. S = superficie moyenne, r = rayon, θ = angle total, C = facteur de correction pour $1m^2$ de section.

Table 1. Cross section of the beam calculated from the comparison between counting and echo-integration. Transects 1 and 10 and figs. into brackets are not included in the average. S: average area, r: radius, θ: full angle, C: normalizing factor for $1m^2$.

Radiales Profondeur	1	2	3	4	5	6	7	8	9	10	S(m^2)	r(m)	θ	C
5-10	0.22	0.31	0.16	0.53	0.41	0.27	0.20	0.67	(1.71)	0.51	0.36	0.34	5^o2	2.78
10-15	0.53	0.60	0.39	0.48	0.41	0.42	0.34	0.54	0.35	0.92	0.44	0.37	3^o4	2.27
15-20	1.03	0.75	0.49	0.58	0.48	0.37	0.53	0.58	0.36	0.58	0.52	0.41	2^o6	1.92
20-25	1.96	3.36	0.99	0.71	0.56	0.40	0.59	0.66	0.76	1.54	0.67	0.46	2^o4	1.49
25-30		(16.38)	0.97	0.90	0.78	0.62	0.74	0.87	0.85	1.50	0.82	0.51	2^o2	1.22
30-35			1.19	0.99	0.82	0.80	0.66	1.25	1.37	1.99	1.01	0.57	2^o0	0.99
35-40			(0.85)	1.62	1.09	1.08	1.25	0.99	0.65	1.23	1.11	0.59	1^o8	0.90
40-50			(0.70)	1.54	1.29	0.57	0.63	0.57	1.57	(0.84)	1.03	0.57	1^o4	0.97
50-60				0.45	0	0.31	0.25	(2.34)	(0.87)	0	0.34	0.33	0^o6	2.94

Inversement pour exprimer le nombre et le poids de poissons évalués par comptage en densité au m^2, il faudra les multiplier par un facteur C tel que :

$$C = \frac{1}{S}$$

On a reporté dans le tableau (1) les valeurs calculées des sections S pour les 10 radiales et par strates de profondeur. On y trouvera également les valeurs moyennes de S pour l'ensemble des radiales, ainsi que le rayon de cette section, l'angle correspondant au faisceau et le facteur C. Pour ces calculs les radiales 1 et 10 et un certain nombre de valeurs aberrantes on été éliminées. La fig. 1 b représente ces sections en fonction de la profondeur.

On remarquera que la courbe ainsi tracée ne diffère pas beaucoup de celle calculée précédemment, la volume maximum de détection paraissant se situer entre 35 et 40 m. Par contre naturellement les valeurs absolues des sections sont beaucoup plus faibles, en accord avec ce qui été dit précédemment.

3. APPLICATION

Ces résultats n'avaient d'intérêt que dans la mesure où ils pouvaient être appliqués à d'autres séries de comptage. Nous avons pu utiliser les données de trois autres sorties qui s'étaient déroulées de facon similaire : les sorties numéros 2, 6 et 10. Les comptages ont été effectués par strate de profondeur de la même manière que pour la sortie 8 bien que certaines densités fussent nettement plus élevées. Deux autres sorties n'ont pu être utilisées car les poissons formaient des bancs.

On a ainsie obtenu un ensemble de couples de valeur de densité variant de 0,1 g/m^3 à près de 10 g/m^3, soit un rapport de 100. En réalité les plus fortes densités étaient bien supérieures puisqu'il s'agit là de valeurs moyennes sur toute une radiale.

Les régressions entre les densités estimées par comptage et par écho-intégration sont parfaitement linéaires. On a groupé ensemble les sorties 6 et 10 et calculé les paramètres de la droite de régression pour 146 couples :

$$\rho c = 0{,}67 + 0{,}88\ \rho i \qquad r^2 = 0{,}95$$

La sortie 2 a été traitée séparément car le gain de l'enregistreur était réglé différemment (voir ci-dessous) :

$$\rho c = 0{,}37 + 1{,}19\ \rho i$$

Les résultats ont été ainsi regroupés par radiale, les points ont été portés sur la fig. 3. L'équation de la droite de régression pour les radiales 6 et 10 s'écrit :

$$\rho c = 6{,}8 + 0{,}82\ \rho i \qquad r^2 = 0{,}98$$

La plupart des points correspondant à la sortie 2 se trouvent nettement au-dessus de la droite. Cette anomalie a été expliquée par le fait que le gain de l'enregistreur était de 1,7 dB de plus que pendant la sortie n° 8.

Cette différence se retrouve dans le calcul des biomasses de la population entière que nous indiquons ci-dessous (en tonnes) :

Sortie	Biomasse (1) comptage	Biomasse (2) écho-intégration	$\frac{(1)}{(2)}$	Gain enregistreur
8	6006	6348	0,95	4,7
2	6074	4588	1,32	6,4
6	8451	7857	1,08	4,6
10	5777	5723	1,01	4,5

On se souviendra que la sortie 8 a servi de base de calcul. Le rôle joué par le gain apparaît nettement dans les résultats de la sortie 2 (non corrigés).

4. DISCUSSION

Les comparaisons entre densités évaluées par comptage sur papier et par écho-intégration portent généralement sur des intervalles sélectionnés et des séries relativement brèves. Au contraire cette étude - et c'est son principal intérêt-traite les données de 4 sorties effectuées sans protocole préalable. Elle a permis de montrer que :

- il existe une très bonne proportionnalité entre densités évaluées par comptage sur papier et par écho-intégration jusqu'à des densités relativement élevées si on utilise un faisceau étroit.

- le volume de détection correspondant à l'enregistrement sur papier dépend étroitement du gain et du seuil de l'enregistreur, sa détermination n'est pas évidente.

- il est possible d'étalonner précisement le système si l'on connaît les densités réelles en poissons aux différentes profondeurs d'utilisation même avec un sondeur dont la fonction GVT est imparfaite ou inadéquate.

- l'évaluation obtenue par compatage dans ces conditions peut être répétée pour autant que les conditions d'utilisatione et la population échantillonnée demeurent stables.

REMERCIEMENTS

Cette étude a été réalisée en partie à l'Université de l'Etat de Washington, College of Fisheries, où j'ai été accueilli par la Professeur O. Mathisen en mai 1978. J'ai pu participer à une sortie et obtenir les résultats d'autres sorties grâce à l'obligeance de M.N. Lemberg du Department of Fisheries.

THE MANAGEMENT OF ACOUSTICS SURVEY DATA FROM THE FIRST BIOMASS EXPERIMENT

by

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ABSTRACT

The acoustics survey part of the First International BIOMASS Experiment is possibly unique in having a project-based system for the international exchange of biological data. and a computer database management and data processing system for the evaluation of data at a Workshop.

In establishing these systems, a data management plan emerged for the standardisation of methods, enforcement of standards, development of international data exchange formats and methods, design of a database, and the development of data processing strategies.

Experience with these aspects of data management at a project level leads to the conclusion that it is possible to exchange raw acoustics survey data at an international level for the purpose of processing and/or archiving for later re-processing.

RESUME

La campagne accoustique de la Première Expérience Internationale BIOMASS est probablement unique, possédant un système d'échange de données informatisées internationales en biologie appartenant à un projet, ainsi qu'un ordinateur de gestion de banque de données informatisées et un système informatique pour l'évaluation dé l'information au cours d'un séminaire.

En établissant ce système, un plan de gestion d'information a pris forme pour la standardisation des méthodes, le contrôle des standards, ainsi que le développement de formats et méthodes d'échanges internationaux de données, qu'un plan de base de données et le développement de stratégie d'informatisation.

L'expérience avec ces deux aspects de gestion de données informatisées au niveau d'un projet indique clairement qu'il est possible d'échanger des informations de campagnes acoustiques au niveau international dans le but de traitement ou d'archivage pour traitement ultérieur.

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1. INTRODUCTION

The research programme known by the acronym BIOMASS is a biological investigation of Antarctic marine ecosystems and stocks. It is a multidisciplinary investigation broadly divided into two main experiments, the First International BIOMASS Experiment, FIBEX (1980/81) and the Second International BIOMASS Experiment (1983/84). The important role of Krill in the Southern Ocean ecosystem was emphasised in the planning of FIBEX as interest grew in a large-scale acoustics survey of part of the Krill stock. The FIBEX acoustics survey ultimately occurred in the West Atlantic, Indian Ocean and a small part of the Pacific sectors of the Southern Ocean, and involved ten research vessels from Argentina, Australia, Chile, Federal Republic of Germany, France, Japan, Poland, South Africa, Union of Soviet Socialist Republics and the United States of America.

Bearing in mind the international and multidisciplinary nature of FIBEX, and BIOMASS as a whole, it became clear a few years ago that the requirement for data sharing required some planning, and that modern data management techniques may be profitably used. In 1978 a small project in multidisciplinary data management was started with Antarctic marine science in mind. The first step was a purely experimental database for managing digital acoustics data. It was called ECHODB, and was described at a hydroacoustics symposium in 1979, (Cram and Mall 1979). The next step was the development of a multidisciplinary database with the capability of managing data from digital and analogue integrators, as well as data from echograms and a wide variety of other data. This was FISHDB, and was described at the ICES 1980 Council Meeting (Cram and Mall 1980). The latest step arose from the decision to hold a Workshop to evaluate some of the results from FIBEX. For this purpose, FISHDB was redesigned and improved, and then named KRILDB for the post-FIBEX Data Interpretation Workshop held in Hamburg during September-October 1981 (Anon 1982). This paper briefly describes how the FIBEX data were managed to create the opportunity for collective international processing at the Workshop.

Because FIBEX was a large international project, the data managers had to face a wide range of problems in data collection methods and standards, data formats, data exchange methods, database design, data processing strategies, system analysis and computer programming. The solutions to these problems are briefly discussed. In general, there are few international agreements or standards covering these aspects of data related to acoustics survey, so FIBEX is possibly unique in having had available to it a project-based system for international exchange of marine biology data, and an advanced data manipulation system for the international co-operative evaluation of the entire data set.

It should be mentioned that, in this paper, the term "database" refers to data stored on computer disc according to a formally-defined database schema, and managed by a programme known as the "database management system". At the post-FIBEX Data Interpretation Workshop the users were communicating interactively with the database management system through the medium of a high-level query programme which prompted the user in plain language on how to proceed with data selection and processing. This provided the users with the means for the continuous, repetitive, selection of any element of the international data set, whilst applying any of a number of processing algorithms to the results of any of the selections.

This paper emphasises that all the intricacies of the development of standards, formats, and so forth, were nothing but a prelude to the amalgamation of the ten sets of data in the database. This was itself only a method of rendering the large quantity of data easily available to the users and allowing them to use the integrated database management system and query programme to process their data quickly and conveniently.

2. PROBLEMS AND SOLUTIONS

The major problems encountered in the management of FIBEX acoustics data are listed below, together with the solutions adopted for FIBEX.

2.1. Calibration procedures were not standard amongst FIBEX participants.

In the absence of internationally-agreed procedures, individuals made a prior agreement to conduct their calibration in a specified manner described in a

BIOMASS Handbook and a report of the BIOMASS Working Party on Acoustic estimation of Krill. An inter-calibration exercise was organised at Arctowski, the Polish base on King George V Island, South Shetland Islands.

2.2. The national teams would collect data according to national procedures.

Informal agreements were reached on standardisation of methods for acoustics, net haul and biological data collection.

2.3. There were no procedures for the international exchange of raw acoustics, net haul and biological data.

A scheme was devised and published as a BIOMASS Handbook.

2.4. There was no previous experience in the amalgamation of raw data from multinational acoustics surveys.

It was believed that a database offered the solution.

2.5. The entire FIBEX acoustics-related data had to be made accessible to all the originators at the same time.

This meant that the data had to be available for extensive processing involving a large number of selections of parts of the multidisciplinary data set, and it all had to be done in the short period when the scientists involved in FIBEX could meet at a Workshop. Once the decision was made to use a database for the storage and retrieval of the data and maintenance of its integrity and the access paths, maximum use could be made of the database facilities for rapid retrieval of any sets of data without programming effort. Processing algorithms were specified by the FIBEX participants, and programmed to make maximum use of the facilities of the integrated database/programming language, PASCAL/R.

3. AGREEMENT ON THE STANDARDISATION OF METHODS

No formal international agreements exist for acoustic survey methodology. Regional, or other co-operative surveys tend to be organised on an ad hoc basis, and FIBEX was no exception. Standardisation was achieved in acoustic and biological methods by BIOMASS Working Parties established partly for this purpose, with the results of their work being published as Reports in the BIOMASS Report Series. In addition, BIOMASS Handbooks were produced for special purposes.

Serious attempts were made at an early stage to establish calibration techniques for FIBEX, and the results were published in a Handbook (Nielsen et al 1980). There were a number of less formal agreements which led to an inter-calibration exercise involving three of the vessels in FIBEX which was held at Arctowski, the Polish Base in the South Shetland Islands. From the methodological side, a Handbook was produced on the methods for scaling the output of an echo-integrator (Ehrenberg 1980) and the Working Party on Acoustic Estimation of Krill produced a number of agreements on measurement methods and definitions concerned with integrator intervals and Krill aggregations (Anon 1980a).

A great effort was made to standardise the relatively complex biological data from net hauls, biological samples, biological data, and length frequencies. In the main, work relevant to acoustics surveys was accomplished by the Working Party on Krill Biology (Anon 1980b), and by the production of a Handbook on biological data collection (Makarov and Denys 1980).

The research teams participating in FIBEX adhered to their agreements remarkably well, even though substantial work was often involved in addition to their own national programmes. Any major departures from the agreements were mostly accidental, where, for example, different standards existed in the literature, or ambiguity existed in descriptions of methods.

4. FIBEX DATA EXCHANGE

Having the acoustics survey methodology informally organised, and having decided to use a database management system as the basis of a Workshop for the international co-operative evaluation of the data, it was necessary to organise the international exchange of raw acoustics survey, and other, data. This entailed developing a data format for exchange purposes, and deciding upon the medium for exchange of the data.

Considerable time and effort has been expended in developing national data collection formats, so it was decided almost immediately that it was impractical to attempt to develop a universally-acceptable "BIOMASS-FIBEX" data collection format. On examining the various national data collection forms or formats, it was apparent that there was a basic core of data which was collected by all, supplemented by various other data to suit national programmes. This was very fortunate,as it was a simple matter to obtain assurances that, for FIBEX, any "missing" data items would be incorporated into the national formats.

It was not possible to allow national groups to send data to the Workshop in national formats, as this would create a vast re-formatting problem. Instead, a data exchange format was developed which took into account the needs of the database, the needs of the data, and, as far as possible, the needs of the users (Cram, 1981). The format for the transmission of data to the Workshop was designed as a series of 80-byte records ordered in a sequence roughly corresponding to the structure of the database. Wherever possible, existing international formats were incorporated into the FIBEX data exchange format to reduce the programming effort in re-formatting. Oceanographic exchange formats and standards are well-known, net haul data forms have tended to look similar due to a process of convergent evolution. The acoustics data needed most attention, and it was decided to develop precise formats for the exchange of abundance data expressed as echo-integrator interval data, or from individual Krill aggregations. A format was developed for multichannel integrators, using any chosen interval length, channel number and width, any units of relative of absolute abundance and any species. The methods were agreed beforehand (see above). The definitions of a Krill aggregation were established and, for each aggregation, the species, depth, thickness, horizontal dimension, and relative or absolute density were recorded. In addition, haul samples were attributed to each integrator interval or aggregation by the originator of the data.

The actual transmission of the data was to be accomplished by magnetic tape, although the format permitted cards to be used. Due to the short period between the development of the exchange format and the occurrence of the Workshop, the originators had their hands full with the data preparation and did not prepare detailed data checking programmes. Normally, the data validation is the responsibility of the originator, but as this was difficult to arrange at short notice, all the validation and correction was done at the Workshop with the aid of the database management system, the database and its query programmes, and specially-written validation programmes.

5. THE ACOUSTICS PART OF THE DATABASE

The database KRILDB and the relational database management system provide the operations for the storage and retrieval of data, maintains the access paths, maintains the physical integrity of the data, schedules transactions on the database, and is responsible for backup and recovery in case of failures. The design of the database KRILDB represents one of possibly many views of the FIBEX data. The object of a successful design is to accurately describe the data, such as echo-integrator interval data and net haul data, in terms of very discrete entities (such as echo-integrator interval position and net haul position) and to define the associations between these entities. This is done to preserve the integrity of the stored data during database activities, such as retrieval, deletion and updating, and to conform to the anticipated needs of query programmes.

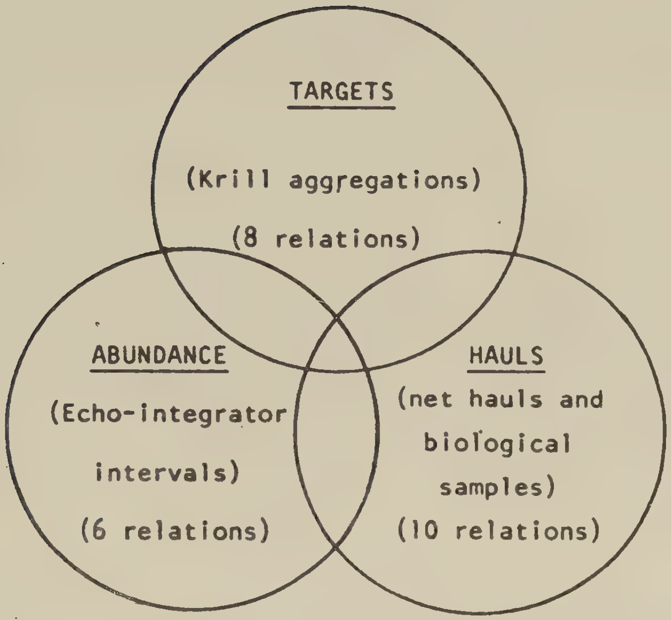


Figure 1 Diagrammatic representation of the part of KRILDB directly concerned with acoustics survey.

The entire KRILDB consists of 81 sets of data entities, called relations: for example "vessel-description", "cruise-tracks", "haul-position", "sample-composition", "aggregation-description", "depth-abundance", "sighting details", "bird-masses", "station-position", "nitrates". Each relation is structured to hold data describing the entities suggested by the relation names, and can be complex (e.g. vessel description), or very simple (e.g. nitrates).

The part of KRILDB directly concerned with entities describing the acoustics survey consists of three major sections of the database, containing 24 relations (see Fig.1). The association between these relations is shown diagrammatically in Fig.2. Note that the hierarchically-arranged diagram represents a relational database. Note also that temporary relations created under control of the programme for storage of data for computation purposes, for "transfer" of data between steps in a programme, for plots, histograms, and tabulations, are not shown.

Each part of the database contains a group of relations, describing the position, date, time and type of the data stored (i.e. aggregation, echo-integrator interval or haul). In the aggregations part (Fig.2a) this basic information is associated with a description of the aggregation (depth, thickness, horizontal dimension and classification). Each aggregation may, or may not, have a number of measured density parameters. This information on the aggregation is supplemented by details associated with the aggregation (usually meteorological or oceanographic information) and by an explicit link to a haul. It is not possible to make a net haul on each aggregation detected in order to obtain biological information, so a decision has to be made to attribute a number of aggregations to a near-by haul. This is a subjective decision best made aboard ship at the time. The basic information on each integrator interval (Fig.2b) is associated with density or abundance

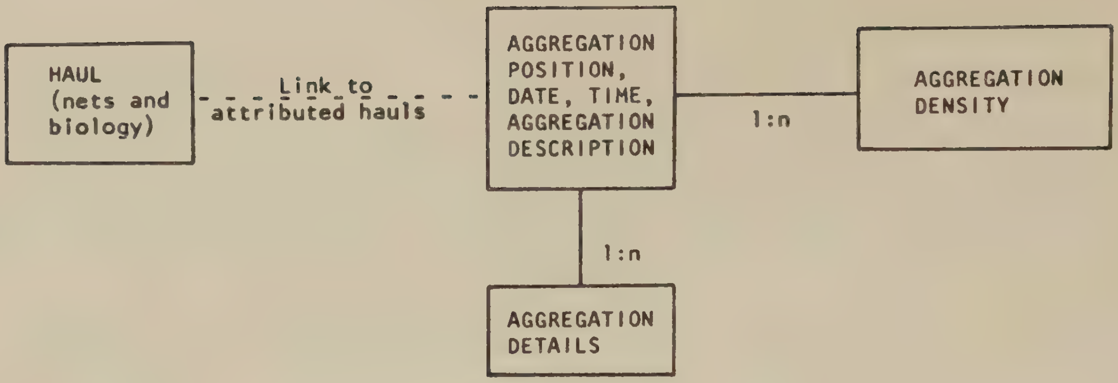


Figure 2a Krill aggregation part of KRILDB (some relations not explicitly shown).

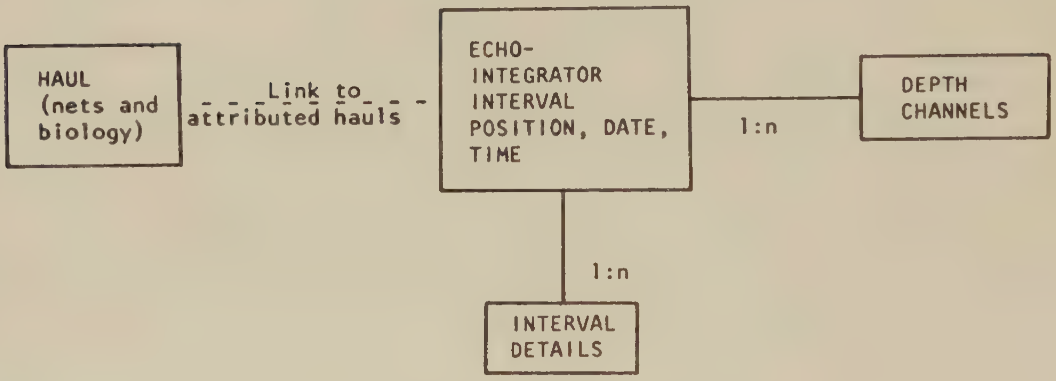


Figure 2b Echo-integrator part of KRILDB (some relations not explicitly shown).

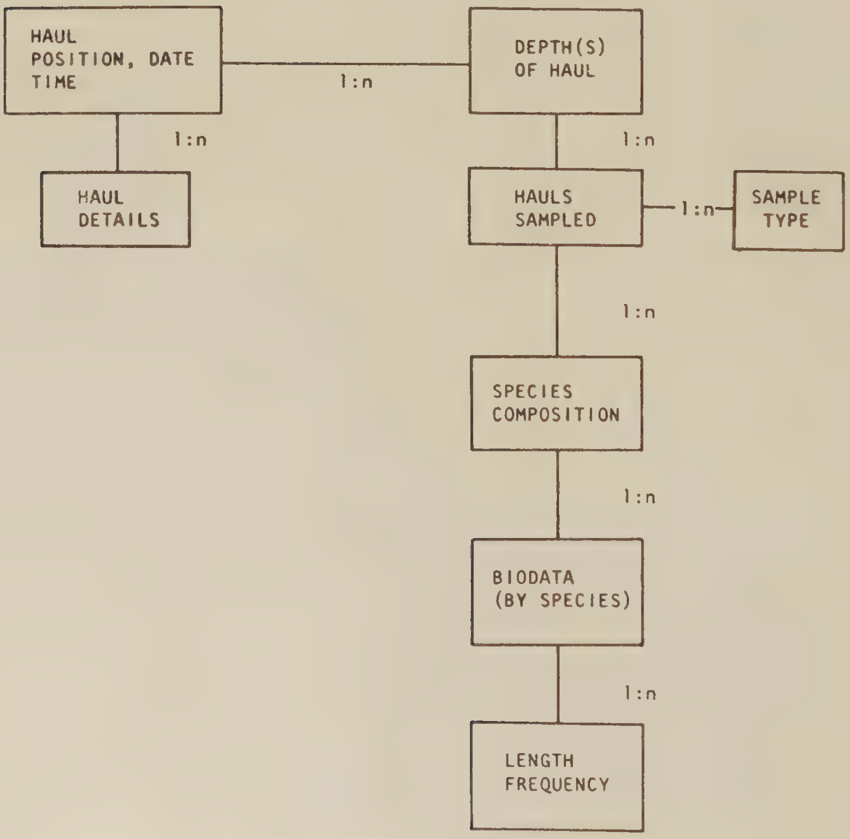


Figure 2c Hauls part of KRILDB (some relations not explicitly shown).

data in any number of depth channels. Again, meteorological, oceanographic or other details can be stored for each interval.

The basic information on net hauls (Fig.2c) is associated with information on how and at what depth the catch was made, including multiple nets fishing at different depths. If there is a catch it will be sampled, so the presence of a sample and its type (weight, volume or number) and the species composition are all recorded. If the sample is analysed, the biological data are stored in one complex relation, and the length frequency data in another. The biodata relation can store any type of biological data usually collected for fisheries-type research. The key for notation in Table 1 is on the last page.

6. ACOUSTIC DATA PROCESSING SYSTEM

The programme suite was written in PASCAL/R which extends the programming language PASCAL by the data structure "relation" and a selection mechanism on relations. The selection mechanism is content-based, which allows the programmer to access data in the database by specifying only the properties of the data of interest. These capabilities make PASCAL/R a powerful and easy to use tool for database-intensive applications where, such as in acoustic data manipulation, complex data sets must be efficiently stored, accessed, and then transformed by sometimes complex algorithms. These facilities have been used extensively, and Table 1 shows the structure of the programme system. Of particular interest is the interface between the query programme and the database, which permits a user to make selections on a data interactively, repetitively, and economically.

6.1. Step 0: Preparations

There were a number of different queries available at the Workshop not concerning acoustics. Initially, a choice had to be made to select the acoustics query. After this, the interactive acoustics query prompts the user on many occasions to provide information on how the computation must proceed (see Table 1). The first prompt is to select an area of interest (a latitude/longitude box), and the date range. The programme then selected the appropriate data from several relations in the KRILDB on the basis of these criteria, and a new temporary relation was created for the duration of the computation. This important database action collected all the data from the relevant integrator intervals, and all the relevant data from net hauls and samples associated with these intervals and stored them in one entity, the "estimation relation". This is very simple in PASCAL/R as there is direct access to any relation (part of the database), and one needs to know nothing about access paths or data structures. Furthermore, when creating a temporary relation, one only has to define the structure of the underlying record, and as many elements of the relation can be inserted as are desired: there are no boundaries as in arrays in PASCAL or FORTRAN.

6.2. Step 1: Computation of mean surface density

The computation of mean surface density $\bar{\sigma}$ (in terms of number) and $\bar{\rho}$ (in terms of weight) is made with the following formulae:

$$\bar{\sigma} = 10^{\frac{\overline{S_v} + 10 \log \Delta R - \overline{TS}}{10}} \qquad (1)$$

$$\bar{\rho} = \bar{\sigma} * \bar{w} \qquad (2)$$

where:

S_v is the mean volume backscattering strength per interval (dB)

$\overline{TS}$ is the mean target strength of krill per interval (dB).

ΔR is the width of integration channel (m),

$\overline{W}$ is the mean weight of krill (mg).

The user is prompted to decide whether target strength ($\overline{TS}$) should be a constant for all selected intervals, or whether the target strength should be automatically calculated for these intervals by the formula:

$$\overline{TS} = a + b * \log \overline{l} \qquad (3)$$

where:

a and b are constants,

$\overline{l}$ is the mean length of krill in samples from appropriate hauls.

If the user decides for a constant target strength, it is immediately entered. Otherwise, the constants a and b must be entered. The constants can be assumed to be the same for all vessels, or must be entered for each of the frequencies used during FIBEX (50, 120 and 200 kHz).

In the original selection of data from the database, the programme tries to attribute a haul to each interval. This is not always possible as, for example, no hauls may have been made. At this point in the programme, the user has to decide whether those intervals to which no hauls can be attributed should be skipped, or if the target strength should be computed with a constant mean krill length ($\overline{l}_c$) entered by the user. If the intervals are not skipped, and the constant krill length entered, a constant mean krill weight must be calculated from the following formula:

$$\overline{w}_c = 0.0018 * \overline{l}_c^{\,-3.383} \qquad (4)$$

The user is then prompted to set a minimum value for volume back-scattering strength ($\overline{S}_V$), for use as a threshold to exclude noise. If the observed values of S_V are less than the threshold, then mean surface density in terms of number ($\bar{\sigma}$) and weight ($\bar{\rho}$) will be set to zero. Following the decisions made at the prompts, mean surface density by number and weight are calculated for each interval, and the estimation relation is updated with these values. This database transaction completes the construction of the estimation relation, which is then available for further steps in the programme. Being a temporary data structure, the estimation relation is deleted after the final computation is completed.

At the end of each "step" in the programme, the user designates the next step. This gives the option of returning to the step just completed and making alterations, or jumping steps.

6.3. Step 2: Display of mean surface density distribition

The user can produce a simple map display of the distribution of intervals with a mean surface density value in terms of number ($\bar{\sigma}$) or weight ($\bar{\rho}$) as calculated during Step 1. The programme prompts the user to select the data to be displayed. As this database transaction is carried out on the estimation relation holding the data selected in Step 0 (the original selection of data), it is only possible to select data from the same latitude/longitude box, or a smaller one. A second temporary relation, the "plot relation" holds the result of the new selection. The user receives three maps: one for each whole 24 hour period in the original date range, one for night and one for day. It is necessary to specify the hours of day.

To produce a clearer map, the mean surface density values are clumped. The clumping algorithm works on a time-sequential basis, so the plot relation is sorted by time. This is easily done by using the key of the relation to enforce the order. In order to cope with gaps in the sequence, the user must specify the maximum time gap acceptable within the clumping algorithm. The mean latitude and longitude values were calculated, and the mean of the mean surface density values obtained from the following formulae:

$$\bar{\sigma}_j = \frac{\Sigma_i \bar{\sigma}_i * D_i}{\Sigma_i D_i} \qquad (5)$$

$$\bar{\rho}_j = \frac{\Sigma_i \rho_i * D_i}{\Sigma_i D_i} \qquad (6)$$

where D_j is the length of the ith interval.

After inspecting the maps, the user can delete some intervals. For example, the day values, the night values, a part of the box, a special time range, or single intervals. This deletion is a transaction carried out on the estimation relation created in Step 0, so any deletion is not recoverable during the current computation.

The user could repeat Step 2 indefinitely, selecting new boxes (always within the original selection in Step 0) and new time ranges for day and night.

6.4. Step 3: Statistics

In Step 3 the user can calculate several statistical properties, either for the whole area (selected in Step 0) or for a newly-selected sub-area, or for a specified time range. The following statistics were calculated for mean surface density either by number or by weight according to the specification of the user:

- number of intervals in the box,
- total sum,
- mode(s),
- median,
- mean (unweighted),
- standard error of mean,
- standard deviation and variance,
- minimum and maximum value,
- range,
- skewness (based on Pearssons formula),
- skewness (based on third moment),
- excess (based on fourth moment),

A histogram of the mean surface density values are also available.

It is worth mentioning again at this point that the results of all computations, such as histograms, graphs, maps, tabulations, and so on, are temporarily stored as relations. This is done to avoid the problems of array boundaries at the interfaces of subroutines which are used by different parts of the query programme, or by other query programmes. This is a very useful feature of the PASCAL/R query language.

6.5. Step 4: Comparison of day and night values of mean surface density by weight.

In order to determine the differences between the computed values of mean surface density from day and night observations, this step allows statistics to be accomplished and selections of the data made on the basis of the results.

As before the user is prompted to select the original area, or a sub-section, and also the range of day and night hours. In addition, a choice has to be made to include integrator values which fall below the preset threshold. The programme then calculates the weighted mean (see formula 6) and the variance for day and night values. Then the Students t-test and its probability α are computed (after checking the variance with an F-test). These results are displayed (and printed if required), and, after inspection, the user can again use a database transaction to delete intervals (cf. Step 2) if, for example, the difference between day and night is significant, and it is necessary to start this step again using different boxes or time ranges.

6.6. Step 5: Estimation of biomass.

Having refined the choice of echo-integrator intervals, the user can start the estimation of biomass within an area. Again, the user is prompted to select an area, either the original box, or a sub-area. Three estimates are provided: for day, night, and 24 hours, so the user must select a time range for day.

The surface area of the selected box is calculated from the formula:

$$A = (L_{2_m} - L_{1_m}) * (G_{2_m} - G_{1_m}) * \cos\left(\frac{L_{2_d} + L_{1_d}}{2}\right) \qquad (7)$$

where:

L_{1m} and L_{2m} are the latitudes in minutes.

L_{1d} and L_{2d} are the latitudes in degrees.

G_{1m} and G_{2m} are the longitudes in minutes.

For the calculation of covariance within transects, the user is prompted to define a transect. This is done by specifying the minimum number of intervals which constitute a transect, and the maximum time gap between intervals permitted within a transect. There was no upper limit on the number of intervals in a transect. If the time gap is too large, a new transect is started. Thus the meaning of "transect" is perforce slightly different from that normally accepted.

Biomass, variance, variance taking into account correlation between integrator values, and variance taking into account correlation within transects are all calculated in Step 5 for day, night and the full 24 hours.

Biomass is calculated with the formula:

$$B_j = A_j * \bar{P}_j = A_j * \frac{\sum_{i=1}^{N_j} \bar{\rho}_{ji} * D_{ji}}{D_{Tj}} \qquad (8)$$

where:

B_j is the biomass in the specified area j,

P_j is the weighted mean weight of krill per unit area in area j,

A_j is the surface area of area j,

N_j is the number of intervals in area j,

$\overline{\rho}_{ji}$ are the mean surface density values by weight in area j,

D_{Tj} is the total integration distance within area j, which is the sum of all integrator interval distances D_{ji}.

Variance ($\mathrm{Var}[B_j]_o$) is calculated with the formula:

$$\mathrm{Var}[B_j]_o = A^2_j \frac{\Sigma_{i=1}^{N_j} (\overline{\rho}_{ji} - \overline{P}_j)^2 \, D^2_{ji}}{D^2_{Tj}} \qquad (9)$$

Recalculated variance ($\mathrm{Var}[Bj]$) taking into account correlation between integrator values is calculated with the formula:

$$\mathrm{Var}[B_j] = \mathrm{Var}[B_j]_o + \frac{8A^2_j}{N^4_j} \Sigma_{K=1}^{N_j-1} \Sigma_{l=K+1}^{N_j} (\overline{\rho}_{jK} - \overline{P}_j)\, (\overline{\rho}_{jl} - \overline{P}_j) \qquad (10)$$

Recalculated variance ($\mathrm{Var}[Bj]_t$) taking into account correlation within transects is calculated with the formula:

$$\mathrm{Var}[B_j]_t = \mathrm{Var}[B_j]_o + \frac{4\ A^2_j}{N^2_j} * \Sigma_{m=1}^{R_j} \frac{\Sigma_{K=1}^{n_m-1} \Sigma_{l=K+1}^{n_m} (\overline{\rho}_{jK} - \overline{P}_j)(\overline{\rho}_{jl} - \overline{P}_j) * n^2_m}{(n_m-1)(n_m-2)} \qquad (11)$$

where:

N_j is the number of intervals in area j,

R_j is the number of transects in area j,

N_m is the number of intervals in transect m.

After inspecting the results, the user must decide if these results should be stored for further computations (Step 6 and 7). Storage is accomplished by creating in the database a temporary relation, the "estimation result relation". Each element of the relation contains all the information on one box. Before the information from a box inserted into this new relation, a check is performed to ensure that the new box does not overlap one already inserted previously. If an overlap is discovered, the user must delete one of the elements of the estimation result relation. If it is decided not to delete, then the information on the overlap is inserted into another temporary relation, the "overlap" relation", for use in Step 7. This is another good example of the database and query language providing simple facilities to solve complex programming problems.

6.7. Step 6: Autocorrelation

Before a user can enter this step, the programme checks that Step 5 has been completed, as the results are required in Step 6. On entering Step 6, the results of the calculations made during each iteration of Step 5 are displayed so that the user can select one for the autocorrelation programme. All this means is that the contents of the estimation result relation (Step 5) are retrieved for display. The user is prompted to specify the conditions for establishing the transects, that is, the maximum permitted gap between intervals. The programme starts to build a transect and stops at the first gap outside the set limit. The number of intervals in this first transect is counted, and if it is less than seven, the user is informed that no autocorrelation is possible, and the programme proceeds to build up the next transect in time sequence. If there are more than six intervals, the user is prompted to specify the maximum number of correlation steps (u in the formula below).

The autocorrelation co-efficient is calculated with the formula:

$$r_{j_u} = \frac{\Sigma_{K=1}^{N_j-u} \; (\overline{\rho}_K - \overline{P}_j)(\overline{\rho}_{K+u} - \overline{P}_j)}{\Sigma_{K=1}^{N_j} \; (\overline{\rho}_K - \overline{P}_j)^2} \qquad (12)$$

where:

r_{ju} is the uth autocorrelation co-efficient in area j.

u is the step size from 1 to the specified level, and for other notation see equation 8.

The results are displayed as a graph with u on the x-axis, and r_{ju} on the y-axis.

The programme runs through all the transects, in sequence, in a box, after which it is possible to re-run the transects again, for example, using a large maximum time interval to increase the length of the transects. Alternatively, a new box can be started. Before proceeding to Step 7, the user must inspect the results of the autocorrelation to find the mean number of steps u_o at which will normally become zero. This value is required in Step 7.

6.8. Step 7: Estimation of total biomass

In this step, the total biomass is computed over all the boxes specified in Step 5. This implies that the user had many iterations of Step 5. It is then necessary to eliminate any over-lapping boxes, to avoid the double inclusion of intervals. When the results of Step 5 (estimation of biomass in an area) were inserted into the estimation result relation, details of over-lapping boxes were inserted into the overlap relation. Step 7 checks to see if the overlapping relation is empty. If not, the total biomass computation cannot proceed until the results from the overlapping boxes have been deleted from the estimation result relation after which it also automatically deleted from the overlap relation. In addition, the user is prompted to insert the mean number of intervals (u_o) from Step 6.

The computation of total biomass is made with the formula:

$$B_T = A * \overline{P} = A * \frac{\Sigma_{j=1}^{M} \overline{P}_j * D_{Tj}}{D_T} \qquad (13)$$

where:

$$A = \Sigma_{j=1}^{M} A_j \qquad (14)$$

$$D_T = \Sigma_{j=1}^{M} D_{Tj} \qquad (15)$$

and M is the total number of boxes.

The computation of variance is made with the formula:

$$\mathrm{Var}[B_T]_o = A^2 \ast \mathrm{var}[\overline{P}] = A^2 \ast \frac{\Sigma_{j=1}^{M} \Sigma_{i=1}^{N_j} (\overline{\rho}_{ji} - \overline{P})^2 \ast D_{ji}^2}{D_T^2} \qquad (16)$$

where:

M is the total number of areas,
N_j is the number of intervals in area j,
$\overline{P}$ is the mean weight of krill per unit area (weighted throughout all areas),
D_T is explained above,

For other notation see equation 8.

The re-calculated variance (taking into account correlation between integrator values) is computed with the formula

$$\mathrm{Var}[B_T] = \mathrm{Var}[B_T]_o + \frac{8\,A^2}{N_T^4} \Sigma_{i=1}^{R} \left(\Sigma_{K=1}^{u_o-1} \Sigma_{l=K+1}^{u_o} (\overline{\rho}_K - \overline{P})(\overline{\rho}_l - \overline{P})\right) \qquad (17)$$

where:

R is the number of interval-series with a length of u_o.

7. ASPECTS OF THE INTERNATIONAL EXCHANGE OF ACOUSTICS DATA

The data exchange system established for FIBEX was arranged on a "regional" basis using informal agreements. The informal agreements were intended to enforce common methods of calibration and data collection, which meant that only the actual echo data were exchanged. Thus the FIBEX acoustics survey data could not be reconstructed or properly evaluated without the presence of those who collected the data and were therefore aware of any departures from agreed methods.

Acoustics survey data can be internationally exchanged. An experiment was conducted during early 1981 using the international oceanographic exchange format GF3 developed by the Working Committee on International Oceanographic Data Exchange (IOC). The contents of a database containing acoustics survey data, net haul and biological sample data and oceanographic data were retrieved, reformatted in GF3, and sent to the United Kingdom National Oceanographic Data Centre with no information other than that the tape was written in GF3 format. The tape was successfully read and the data exchange was therefore successful in principle (IODE/IOC Summary Report, 1981). Nevertheless, the data suffered from the same disadvantage as the FIBEX data, namely that the calibration and data collection information were lacking, so that the data could not be used by a third party.

Experience with FIBEX has shown that it is quite feasible to relate calibration data and equipment settings to individual echo-integrator intervals or individual aggregations in much the same way as haul data were attributed to these data. Other useful pointers towards standardisation for international data exchange emerged from the work done by FIBEX participants at the Workshop. The acoustics group recommended that all abundance data should be exchanged in units of volume back-scattering strength; that the standard reporting interval for integrators should be one mile; that multichannel integrators should be set to channels in multiples of 10 metres, referenced to the transducer. An important aspect for database design is the recommendation that data be accessed by transducer frequency, and that each transect be identified by the originator and accessed directly within the database (Anon. 1982).

Experience with FIBEX shows that there are no problems, in principle, preventing the development of international data exchange methods for acoustic survey data.

8. CONCLUSIONS

The system which has been described represents the third stage of an informal development programme. The first stage, ECHODB, was purely experimental and had no query programme associated with it. The second stage, FISHDB, was semi-operational, using real test-data, possessing a suite of simple query programmes, but possessing no data input or data checking facilities and only primitive output. The third stage, KRILDB, is operational, and possesses a range of data input and checking systems, a complex query programme suite and a range of output data products. The development process can be carried further by re-designing the database to take into account more sophisticated data types and processing algorithms.

Each stage in the evolution of the system demanded a higher degree of data organisation and validation by the originator. ECHODB demanded nothing except the ability to invent a small amount of plausible data; FISHDB accepted the originators'data in any form and any state of accuracy; KRILDB demanded rigid adherence to formats and standards. Undoubtedly, rigid adherence to formats and standards requires hard work, but the rewards were available for FIBEX both in the short-term and in the long-term. The effort expended in data collection to unfamiliar standards, reformatting the data to an unfamiliar format, transmission of the data to another institute, correction of data, and its insertion into the database were rewarded in the short-term by the creation of the conditions for international co-operative processing of the data at a Workshop. In the long-term, this effort is not lost: the data set remains intact and can be used for future Workshops without any further effort by the originators. If they wish, the data can be augmented or re-structured to suit new ideas. Perhaps the greatest long-term advantage is that an operational system for the management of acoustics data is now in existence, and is available for future use.

Whilst the overall management of the FIBEX acoustic data includes the organised effort of the data originator, much of the purpose of the originators' effort was to prepare data for insertion into a database. The value of the database seems proven: standards were enforceable, the data were merged into a coherent entity, and processing programmes had access to any combination of data in the database. The integrated database management system and programming language, PASCAL/R, provided a relatively simple, yet highly sophisticated, method of manipulating the data. This advantage was most strongly felt by the user who wishes to make large numbers of different selections of different data, whilst applying a complex processing algorithm to the results of each selection. It is particularly interesting to note that the database design was changed during the Workshop when the users were forced to change ths structure of one item of data. This had no impact on the query programmes and did not interrupt the flow of work. Having an international database, the processing programmes tend to be developed co-operatively, or at least by consensus, which leads to the results achieving widespread acceptability.

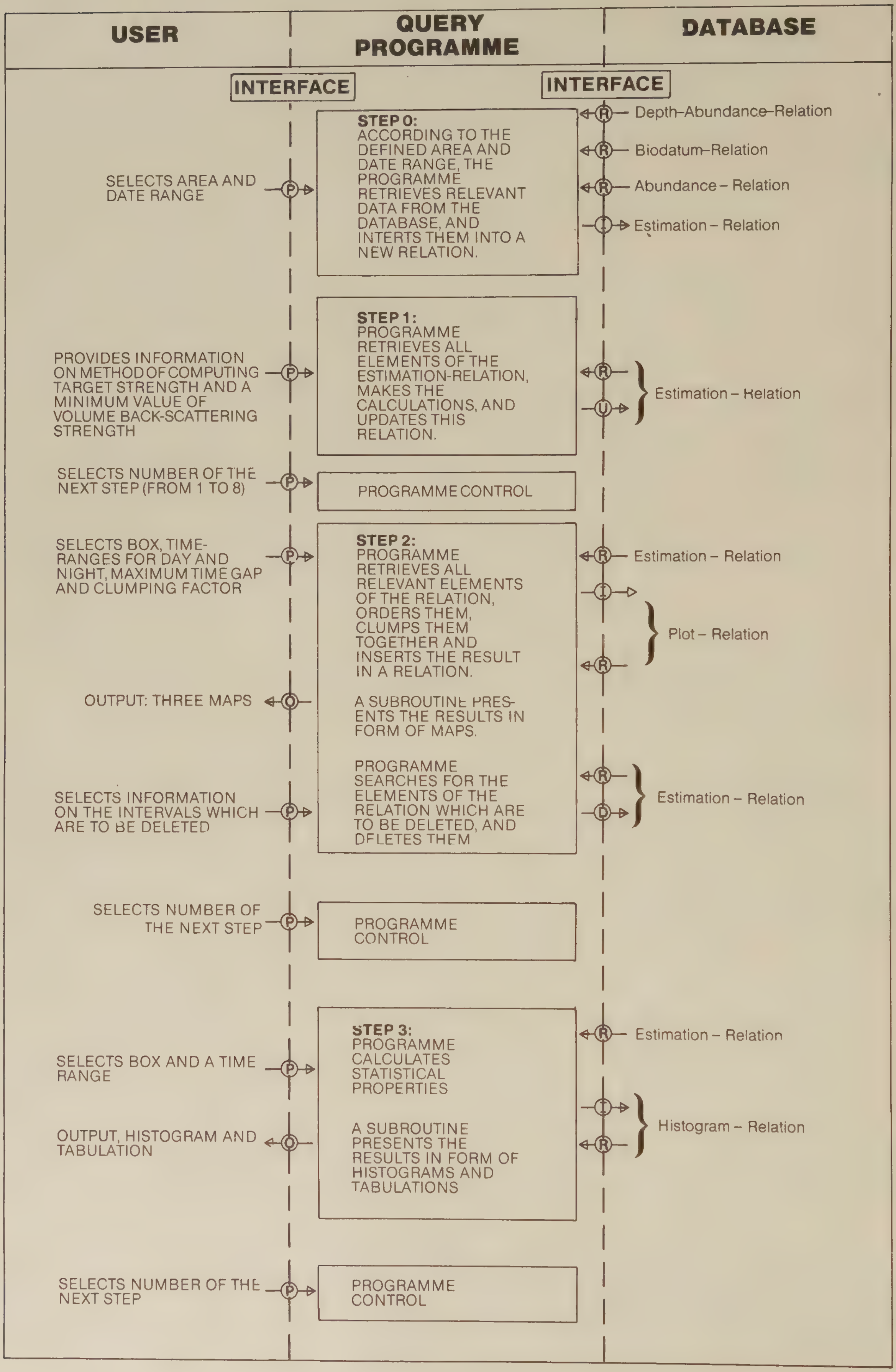
The data management system for FIBEX worked well, chiefly because the originators of the data adhered to informal agreements. Wider international exchange of acoustics survey data is also possible, but must be independent of personal or regional agreements. The basis of such an international system could easily be established and, if there is a Workshop for the second international BIOMASS experiment (SIBEX), it may be possible to carry out a full scale experiment in international acoustics survey data exchange.

It is a legitimate question to ask if the level of sophistication in data management described in this paper is too high, and hence too expensive, to be of any practical use to fisheries research or other related fields. An interesting development in marine science is the frequency with which major investigations now occur, and BIOMASS is no exception: FIBEX, a major investigation involving 10 research vessels, ended in April 1981 and the second BIOMASS experiment, SIBEX, will start in December 1983. One of the objects of FIBEX data management was to ensure that enough results of FIBEX were available to plan SIBEX effectively. The Workshop was held roughly 6 months after the end of FIBEX and produced a useful selection of results two years before SIBEX is due to start. This probably would not have been possible without a plan for data management and the production of results. The experience gained with FIBEX will benefit SIBEX and it is hoped that the ideas and concepts employed will be of interest to fish stock managers who have rigid deadlines for the provision of management advice, and forsee a situation where large-scale acoustic surveys will have to be conducted at very closely spaced intervals of time, with the results having to be produced by relatively few people.

9. ACKNOWLEDGEMENTS

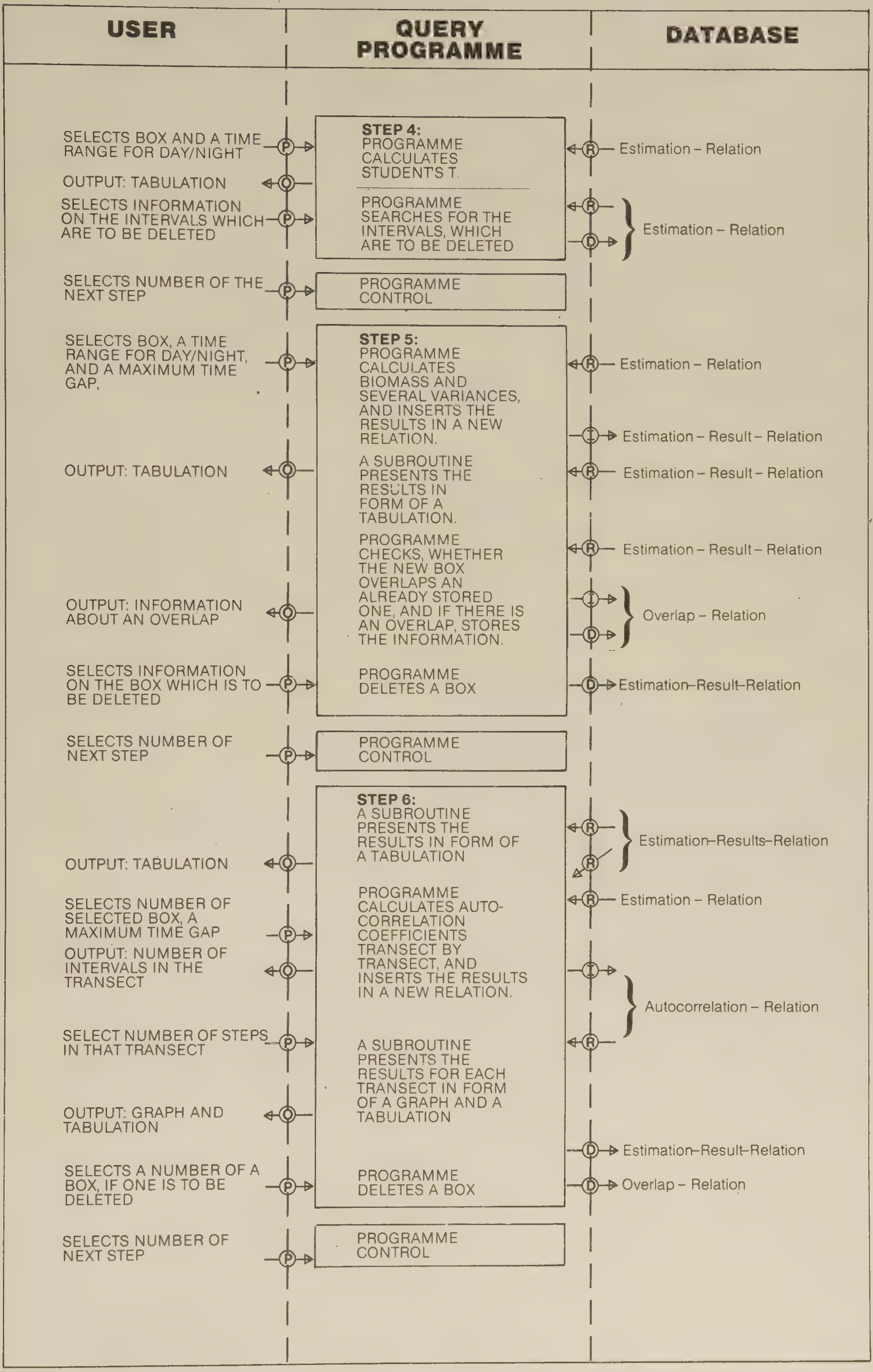
We would like to thank many colleagues for their advice and help during the period of development described here, especially those in the Department of Computer Science at the University of Hamburg. During the post-FIBEX Workshop, many constructive comments were made by colleagues and, in the main, these were faithfully recorded as recommendations in the Workshop Report. However, we would like to record our appreciation of helpful criticism from the colleagues who were involved in FIBEX and who may not have attended the Workshop.

Table 1 Relationships between the user of the system, the query programme and the database. The key to the notation is on the last page.



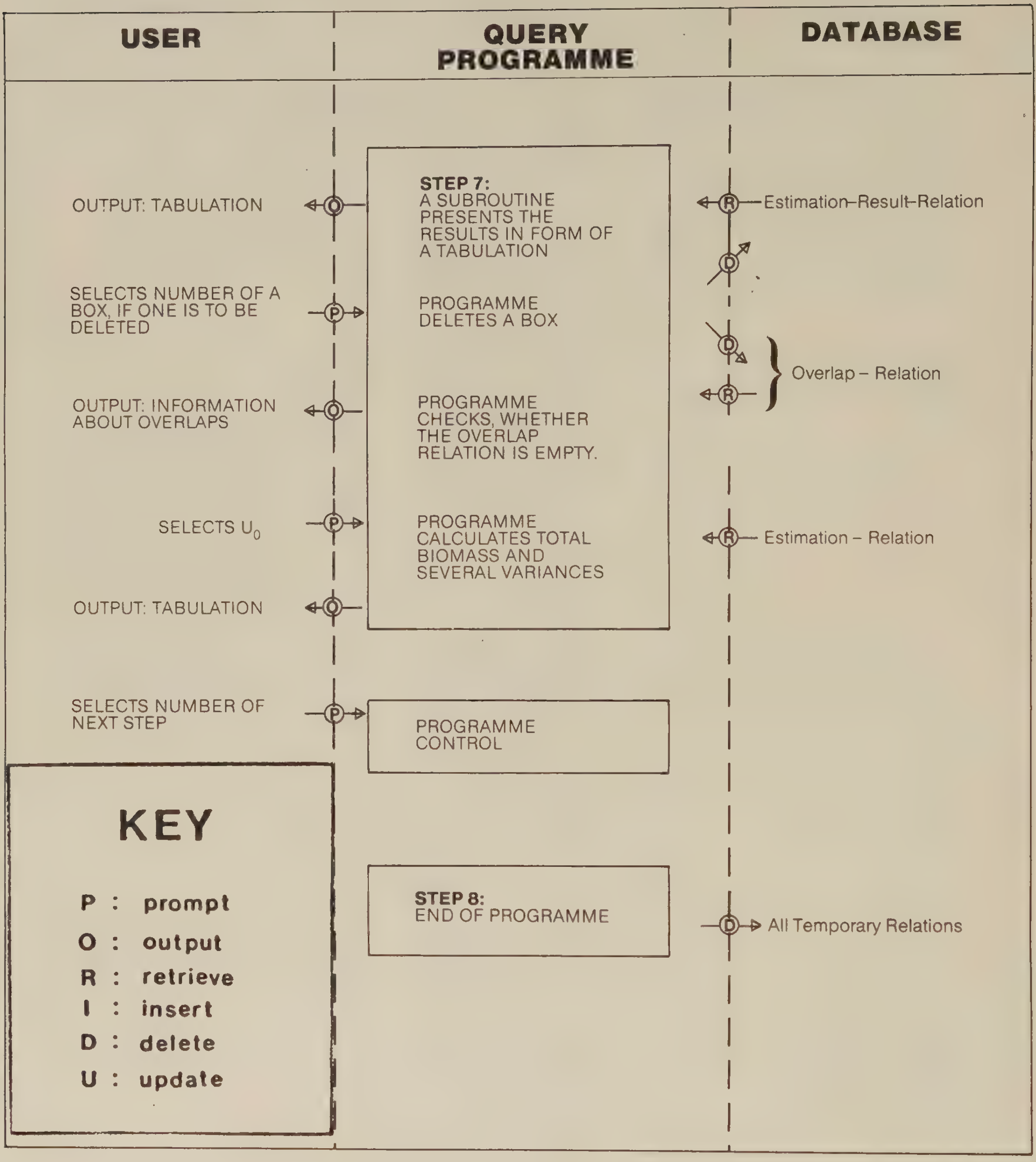
USER	INTERFACE	QUERY PROGRAMME	INTERFACE	DATABASE
SELECTS AREA AND DATE RANGE	—Ⓟ→	**STEP 0:** ACCORDING TO THE DEFINED AREA AND DATE RANGE, THE PROGRAMME RETRIEVES RELEVANT DATA FROM THE DATABASE, AND INTERTS THEM INTO A NEW RELATION.	←Ⓡ— ←Ⓡ— ←Ⓡ— —Ⓘ→	Depth–Abundance–Relation Biodatum–Relation Abundance – Relation Estimation – Relation
PROVIDES INFORMATION ON METHOD OF COMPUTING TARGET STRENGTH AND A MINIMUM VALUE OF VOLUME BACK-SCATTERING STRENGTH	—Ⓟ→	**STEP 1:** PROGRAMME RETRIEVES ALL ELEMENTS OF THE ESTIMATION-RELATION, MAKES THE CALCULATIONS, AND UPDATES THIS RELATION.	←Ⓡ— —Ⓤ→	Estimation – Relation
SELECTS NUMBER OF THE NEXT STEP (FROM 1 TO 8)	—Ⓟ→	PROGRAMME CONTROL		
SELECTS BOX, TIME-RANGES FOR DAY AND NIGHT, MAXIMUM TIME GAP AND CLUMPING FACTOR	—Ⓟ→	**STEP 2:** PROGRAMME RETRIEVES ALL RELEVANT ELEMENTS OF THE RELATION, ORDERS THEM, CLUMPS THEM TOGETHER AND INSERTS THE RESULT IN A RELATION.	←Ⓡ— —Ⓘ→ ←Ⓡ—	Estimation – Relation Plot – Relation
OUTPUT: THREE MAPS	←Ⓞ—	A SUBROUTINE PRESENTS THE RESULTS IN FORM OF MAPS.		
SELECTS INFORMATION ON THE INTERVALS WHICH ARE TO BE DELETED	—Ⓟ→	PROGRAMME SEARCHES FOR THE ELEMENTS OF THE RELATION WHICH ARE TO BE DELETED, AND DELETES THEM	←Ⓡ— —Ⓓ→	Estimation – Relation
SELECTS NUMBER OF THE NEXT STEP	—Ⓟ→	PROGRAMME CONTROL		
SELECTS BOX AND A TIME RANGE	—Ⓟ→	**STEP 3:** PROGRAMME CALCULATES STATISTICAL PROPERTIES	←Ⓡ—	Estimation – Relation
OUTPUT, HISTOGRAM AND TABULATION	←Ⓞ—	A SUBROUTINE PRESENTS THE RESULTS IN FORM OF HISTOGRAMS AND TABULATIONS	—Ⓘ→ ←Ⓡ—	Histogram – Relation
SELECTS NUMBER OF THE NEXT STEP	—Ⓟ→	PROGRAMME CONTROL		

Table 1 (Continued)



USER	QUERY PROGRAMME	DATABASE
SELECTS BOX AND A TIME RANGE FOR DAY/NIGHT —(P)→	**STEP 4:** PROGRAMME CALCULATES STUDENT'S T.	←(R)— Estimation – Relation
OUTPUT: TABULATION ←(O)—		
SELECTS INFORMATION ON THE INTERVALS WHICH ARE TO BE DELETED —(P)→	PROGRAMME SEARCHES FOR THE INTERVALS, WHICH ARE TO BE DELETED	←(R)— —(D)→ } Estimation – Relation
SELECTS NUMBER OF THE NEXT STEP —(P)→	PROGRAMME CONTROL	
SELECTS BOX, A TIME RANGE FOR DAY/NIGHT, AND A MAXIMUM TIME GAP, —(P)→	**STEP 5:** PROGRAMME CALCULATES BIOMASS AND SEVERAL VARIANCES, AND INSERTS THE RESULTS IN A NEW RELATION.	←(R)— Estimation – Relation —(I)→ Estimation – Result – Relation
OUTPUT: TABULATION ←(O)—	A SUBROUTINE PRESENTS THE RESULTS IN FORM OF A TABULATION.	←(R)— Estimation – Result – Relation
OUTPUT: INFORMATION ABOUT AN OVERLAP ←(O)—	PROGRAMME CHECKS, WHETHER THE NEW BOX OVERLAPS AN ALREADY STORED ONE, AND IF THERE IS AN OVERLAP, STORES THE INFORMATION.	←(R)— Estimation – Result – Relation —(I)→ —(D)→ } Overlap – Relation
SELECTS INFORMATION ON THE BOX WHICH IS TO BE DELETED —(P)→	PROGRAMME DELETES A BOX	—(D)→ Estimation–Result–Relation
SELECTS NUMBER OF NEXT STEP —(P)→	PROGRAMME CONTROL	
OUTPUT: TABULATION ←(O)—	**STEP 6:** A SUBROUTINE PRESENTS THE RESULTS IN FORM OF A TABULATION	←(R)— (R) } Estimation–Results–Relation
SELECTS NUMBER OF SELECTED BOX, A MAXIMUM TIME GAP —(P)→	PROGRAMME CALCULATES AUTO-CORRELATION COEFFICIENTS TRANSECT BY TRANSECT, AND INSERTS THE RESULTS IN A NEW RELATION.	←(R)— Estimation – Relation
OUTPUT: NUMBER OF INTERVALS IN THE TRANSECT ←(O)—		—(I)→ } Autocorrelation – Relation
SELECT NUMBER OF STEPS IN THAT TRANSECT —(P)→	A SUBROUTINE PRESENTS THE RESULTS FOR EACH TRANSECT IN FORM OF A GRAPH AND A TABULATION	←(R)— } Autocorrelation – Relation
OUTPUT: GRAPH AND TABULATION ←(O)—		
SELECTS A NUMBER OF A BOX, IF ONE IS TO BE DELETED —(P)→	PROGRAMME DELETES A BOX	—(D)→ Estimation–Result–Relation —(D)→ Overlap – Relation
SELECTS NUMBER OF NEXT STEP —(P)→	PROGRAMME CONTROL	

Table 1 (Continued)


USER
QUERY PROGRAMME
DATABASE
OUTPUT: TABULATION
O
STEP 7: A SUBROUTINE PRESENTS THE RESULTS IN FORM OF A TABULATION
R
Estimation–Result–Relation
D
SELECTS NUMBER OF A BOX, IF ONE IS TO BE DELETED
P
PROGRAMME DELETES A BOX
D
R
Overlap – Relation
OUTPUT: INFORMATION ABOUT OVERLAPS
O
PROGRAMME CHECKS, WHETHER THE OVERLAP RELATION IS EMPTY.
SELECTS U$_0$
P
PROGRAMME CALCULATES TOTAL BIOMASS AND SEVERAL VARIANCES
R
Estimation – Relation
OUTPUT: TABULATION
O
SELECTS NUMBER OF NEXT STEP
P
PROGRAMME CONTROL
STEP 8: END OF PROGRAMME
D
All Temporary Relations
KEY
P : prompt
O : output
R : retrieve
I : insert
D : delete
U : update

EVALUATION ACOUSTIQUE DE LA BIOMASSE DES STOCKS DE SARDINE AU MAROC DE 1979 à 1981. COMBINAISON DES ESTIMATIONS DU SONAR ET DU SONDEUR VERTICAL

par

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RESUME

Quatre prospections acoustiques effectuées le long de la côte atlantique marocaine, ont permis de couvrir entre 1979 et 1981 la zone de répartition de la sardine, Sardina pilchardus. Les estimations de biomasse ont été obtenues par combinaison de la partie superficielle de la biomasse détectée par le sonar, et la partie plus profonde détectée par le sondeur vertical. La méthodologie employée et les résultats obtenus pour quatre prospections sont présentés et discutés.

SUMMARY

Four acoustic surveys have been carried out along the atlantic coast of Morocco. The distribution area of the stock of sardines Sardina pilchardus was covered during the period from 1979 to 1981. The estimates were obtained by combining the superficial part of the biomass detected by the sonar, and the deeper part detected by the vertical sounder. The method and results obtained for four surveys are presented and discussed.

1. INTRODUCTION

Le programme de prospections acoustiques au Maroc est réalisé par l'Institut scientifique des pêches maritimes, avec l'assistance du projet FAO/Norvège GCP MOR/008/NOR et du projet PNUD/FAO MOR 78/018. Son but est d'estimer la biomasse des stocks de poissons pélagiques le long des côtes marocaines. Au total quatre prospections acoustiques ont été réalisées de 1979 à 1981 (en novembre 1979, en juillet et novembre 1980, et en octobre 1981) visant à estimer la biomasse de la sardine (Sardina pilchardus), espèce pélagique principale le long des côtes marocaines, et à suivre son évolution. Dès les premières campagnes, il est apparu que les biomasses calculées sur la base des données obtenues au moyen du sondeur vertical et de l'échointégrateur étaient sous-estimées. En effet, la distribution verticale des sardines indique qu'une grande partie des concentrations est située près de la surface, c'est à dire dans une zone que le sondeur vertical ne couvre que partiellement. Pour remédier à cet inconvénient, les estimations de la biomasse des sardines ont été calculées en combinant les données obtenues de la couche superficielle au moyen du sonar, avec celles obtenues des couches plus profondes au moyen du sondeur vertical et de l'échointégrateur.

La méthodologie utilisée dans la présente étude permet de combiner les données obtenues des deux sources. Cette méthode, inspirée de celle décrite par Smith (1970), a déjà été décrite par Bazigos et al. (1980), elle a ensuite été modifiée et améliorée pour le traitement des données du sonar, et la combinaison des données du sonar et de l'échointégrateur. Le jeu de programmes de traitement des données sur ordinateur de bureau Hewlett Packard 9845, a été préparé par R. Coppola (sous presse).

2. REGION COUVERTE ET STRATEGIE DE PROSPECTION

Les prospections acoustiques exécutées ont couvert le Maroc atlantique du Cap-Cantin (32°33'N) au Cap Blanc (20°40'N), de l'isobathe 10-15 m à l'isobathe 100-200 m, de facon à prospecter la majorité de l'aire de répartition des sardines, voir Fig. 1.

Le plan d'échantillonnage suit un parcours en radiales parallèles perpendiculaires aux isobathes lorsque la largeur du plateau continental dépasse 20 milles, et un parcours en zig-zag dans les régions où celui-ci est plus étroit. La distance entre les radiales est de 20 milles. L'effort de prospection est plus intense sur les fonds de 15 à 80 mètres, pour tenir compte de la distribution des sardines.

Le sondeur vertical couplé à l'échointégrateur fournit des informations sur la densité des concentrations de poissons situées sous le bateau, et le sonar permet de compter les bancs qui se présentent sur le coté du bateau. Les données sont enregistrées par mille parcouru. Des opérations de pêche permettant d'identifier les échotraces et de prélever des échantillons biologiques sont effectués régulièrement.

3. CHARACTERISTIQUES DES DONNEES BRUTES

3.1 Données du sondeur vertical et de l'échointégrateur

Le tableau ci-dessous montre que la distribution verticale du centre de gravité des concentrations de poissons, obtenue à partir des données du sondeur, ne correspond pas à ce que l'on observe dans la réalité chez la sardine qui est fréquemment située prés de la surface.

Pourcentage d'observations en fonction de la profondeur d'immersion du centre de gravité des concentrations de sardines. Données du sondeur de jour Novembre 1979.

Profondeur	2	7	12	17	22	27	32	37	42	47	52	57	62	67	72	77
pourcentage	0	0	3	10	29	19	14	7	5	1	4	4	3	0	1	0

En effet, la densité de poissons est nulle dans les premiers mètres d'eau, alors que des bancs peuvant etre observés en surface à l'oeil nu. Les données obtenues au moyen du sondeur vertical sont donc biaisées. On peut définir trois sources de biais, deux d'origine physique ou technique et une liée au comportement des poissons:

a) La position du transducteur du sondeur sur la coque ne permet pas d'enregistrer les échos de poissons en provenance de la zone située entre la surface et la profondeur d'immersion du transducteur.

b) Une particularité des sondeurs utilisés pour les besoins des estimations acoustiques quantitatives est qu'ils sont épuipés d'un systéme de TVG (Gain variable en fonction du temps) qui permet de compenser les effets de la dispersion et de l'absorption du son dans l'eau. Ce système n'est pas immédiatement opérationnel au voisinage du transducteur, et il ne commence en fait à agir qu'à une distance de 3 à 4 mètres à partir de ce dernier. Les informations obtenues à partir des premiers mètres porches du transducteur sont ainsi biaisées.

c) Le passage du bateau, les remous qu'il provoque et le bruit des moteurs, entrainent des réactions d'évitement de la part du poisson vers le fond ou vers les côtés. L'importance de ces réactions est fonction de la distance au bateau, et varie selon que les poissons sont plus actif lorsqu'ils sont groupés en bancs durant le jour, ou moins actifs lorsqu'ils sont dispersés pendant la nuit.

En resumé le sondeur vertical fournit des informations que l'on peut considérer comme exemptes de biais à partir d'une profondeur de 15 à 20 mètres de la surface et ne nous fournit aucune donnée entre la surface et la profondeur d'immersion du transducteur sur la coque.

3.2 Données du sonar

Le sonar, dirigé horizontalement selon un angle de 90° avec l'axe de déplacement du navire, permet d'échantillonner les bancs de poissons situées d'un coté ou de l'autre du bateau.

La propagation du son à l'horizontale est perturbée par la structure thermique des couches d'eau; en particulier, le faisceau sonore est incurvé vers le bas dans le cas de gradients de température négatifs de la surface vers le fond. Le sonar ne peut donc pas être utilisé de la même manière que le sondeur vertical raccordé à un echointégrateur car, il est difficile de déterminer le volume d'eau échantillonné. L'écho des poissons se mêle à des échos en provenance de la surface, ou du fond si les eaux sont peu profondes. Dans ces conditions, les concentrations de poissons dispersés ou de faibles densité ne sont pas discernables sur le sonar, et seuls les bancs de densité suffisante donneront un écho. Ainsi, seules les données de jour sont exploitables car les sardines sont regroupées en bancs, alors qu'elles sont dispersées la nuit. Là encore des limitations interviennent lorsque les bancs sont situés très près du fond; il est alors parfois difficile de les distinguer si leur densité est faible.

En définitive, le sonar ne fournit d'informations que sur la densité en termes de nombre de bancs par unité de surface balayée, et non en termes de quantité de poissons par unité de surface, car il ne permet pas de déterminer la densité à l'intérieur des bancs. De plus, il est possible de mesurer la distance à laquelle les bancs sont détectés et leur dimension horizontale.

Il convient de noter que le nombre de bancs par unité de surface balayée donné par le sonar est biaisé, et ne reflète donc pas exactement la réalité. Les sources de biais sont de trois ordres. La première, liée aux phénomènes d'évitement des bancs de poisson au passage du bateau, peut entrainer une surconcentration de ces derniers au voisinage immédiat du navire. La deuxième est liée au fait que le faisceau sonore est de section conique; il en découle que dans le plan vertical, la profondeur de la tranche d'eau échantillonné augmente au fur et à mesure que l'on s'éloigne du bateau (Fig. 2), et dans le plan horizontal la zone proche du bateau dont la largeur est fonction de sa vitesse et de la fréquence de récurrence des émissions sonar, est incomplètement échantillonnée. La troisième source de biais, liée aux phénomènes de dispersion géométrique de l'energie dans le faisceau sonore et à l'atténuation du son dans l'eau, fait que les bancs sont moins bien détectés au fur et à mesure que l'on s'éloigne du bateau; ce phénomène a lieu d'autant plus près du bateau, que les bancs sont de taille plus petite ou de densité plus faible.

Les données sonar finalement prises en considération sont sélectionnées dans un intervalle de distances par rapport au bateau dans lequel on considère qu'elles sont les moins entachées de biais. La méthode de détermination de cet intervalle appelé "portée efficace du sonar", est décrite plus loin.

4. TRAITEMENT DES DONNEES

Après ces considérations sur la qualité et la validité des données obtenues à partir du sondeur vertical et de l'échointégrateur d'une part, et sur celles obtenues à partir du sonar d'autre part, nous allons envisager maintenant la méthodologie utilisée pour le traitement des données et la combinaison des estimation obtenues à partir de l'échointégrateur et du sonar.

4.1 Biomasse détectée par le sonar

Pour déterminer la biomasse détectée par le sonar, il est nécessaire de connaitre:

1) le volume d'eau échantillonné,
2) la "portée efficace" du sonar dans laquelle les erreurs d'échantillonnage sont considérées minimum,
3) la densité des bancs par unité de surface calculée en tenant compte des deux paramètres précédents,
4) le poids moyen d'un banc.

4.1.1 Volume d'eau échantillonné par le sonar.

Le volume d'eau échantillonné par le sonar est surtout fonction de l'angle vertical d'ouverture du faisceau sonore car, dans le plan horizontal, la vitesse du bateau et la fréquence de récurrence des émissions sont telles que sauf dans la région très proche du bateau, les surfaces correspondant à chaque transmission sonar se chevauchent (Fig. 2).

L'angle vertical du faisceau sonar qui nous intéresse est celui pour lequel les bancs rencontrés fournissent un écho, or cet angle est fonction de propriétés réfléchissantes des cibles. L'énergie sonore décroit, au fur et à mesure que l'on s'éloigne de l'axe du faisceau, et les bancs de poissons sont moins bien détectés. Le seuil de détection varie avec la densité des bancs et ceux de faible densité seront les premiers à ne plus fournir d'échos en s'éloignant de l'axe du faisceau. On a donc mesuré l'angle vertical d'ouverture du faisceau sonar en fonction des propriétés réfléchissantes des bancs de sardines. Pour cela, une méthode très simple a été utilisée: le faisceau du sonar étant dirigé vers l'avant du bateau, on compare la distance à laquelle un banc cesse d'etre détecté par le sonar, avec la profondeur à laquelle ce même banc est détecté sur le sondeur vertical (Fig. 3). Ceci implique que le banc n'ait pas effectué de mouvement dans le sens vertical entre le moment où le contact a été perdu avec le sonar, et celui où il a été établi avec le sondeur vertical. Le faisceau du sondeur vertical étant beaucoup plus étroit que celui du sonar, les bancs détectés au sondeur vertical correspondent à ceux qui se situaient au centre du faisceau sonar dans l'axe du navire.

Par construction géométrique, on peut déterminer la position de la limite inférieur du faisceau sonar et calculer son demi angle d'ouverture verticale.

$$D'_E = D_E - D$$

$$\frac{D'_E}{D_S} = \sin\left(\frac{A}{2} + B\right)$$

$$\frac{A}{2} = \left(\arcsin \frac{D'_E}{D_S}\right) - B$$

où D_E = Profondeur du banc lue sur le sondeur vertical (m.)

D = Différence de profondeur entre les transducteurs du sonar et du sondeur vertical. (m.)

D_S = Distance correspondant au dernier contact du banc sur le sonar.

D'_E = Profondeur du banc par rapport au transducteur du sonar (m.)

$\frac{A}{2}$ = Demi angle d'ouverture du faisceau sonar (degrés)

B = Angle d'inclinaison de l'axe du faisceau sonar par rapport à l'horizontale (degrés).

Le résultat obtenu pour les bancs de sardines varie de 10,4° à 11,4°. Les valeurs correspondent environ au double de la valeur de l'angle compris entre les points 3dB, donnée par le constructeur.

L'utilisation de cette méthode permet de tenir compte des variations éventuelles dans les performances du sonar et dans le pouvoir de réflection des cibles. On peut ainsi déterminer plusieurs angles d'ouverture pour différentes régions et tenir compte des variations de la taille et de la densité des bancs.

4.1.2 Portée efficace du sonar

Pour pallier les biais qui affectent la qualité des données fournies par le sonar on a cherché à déterminer une zone dans laquelle les mesures peuvent etre considérées comme non entachées de biais.

Si l'on considère que les bancs sont distribués de facon homogène dans le plan horizontal, un sonar idéal dirigé sur le coté du navire permettrait de détecter ces bancs de facon équivalente indépendamment de leur distance par rapport au navire et de leur pouvoir de réflection. La représentation du nombre de bancs détectés par mille parcouru en fonction de leur distance par rapport au bateau, donnerait dans ce cas une distribution en plateau (Fig. 4A). Dans la pratique on obtient des courbes assymétriques et la proportion de bancs détectés augmente rapidement à partir d'une faible distance du bateau, passe par un maximum, puis décroit lentement lorsque l'on s'éloigne du navire. L'aspect de ces courbes réelles est lié aux trois sources de biais déjà citées: variations du volume échantillonné en fonction de la distance, variation du seuil de détection des bancs en fonction de leur éloignement et de leurs propriétés réfléchisantes, et surconcentration des bancs trés proches du bateau, liée aux réactions d'évitement.

Sur les courbes réelles du type de celles de la Fig. 4A, il est malaisé de définir une portion de la distribution qui se rapproche le plus d'une distribution en plateau. On a alors tracé les mêmes distributions en pourcentage cumulé du nombre de bancs détectés en fonction de la distance (Fig. 4B); la courbe obtenue à partir du sonar idéal devient une droite, alors que les courbes réelles deviennent des courbes en "S" qui présentent une portion ascendante plus au moins recltiligne. On considère que cette portion rectiligne correspond à la plage pour laquelle le fonctionnement du sonar se rapproche le plus des conditions idéales. A partir d'exemples observés présentés sur la Fig. 5, on peut voir que la portion rectiligne des courbes cumulées peut être assimilée avec une bonne approximation à la zone comprise entre les distances pour lesquelles 25 et 75% des bancs sont détectés.

Il est intéressant d'observer la distance à laquelle 50% des bancs sont détectés. Dans les conditions idéales cette distance devrait se situer au centre de celles correspondant aux points 25 et 75%. Si l'on tient compte du fait que le volume échantillonné croit avec la distance, le point 50% devrait se situer à une distance qui corresponde à l'égalité des deux volumes échantillonnés V_1 et V_2 (Fig. 6). Le point 50% devrait se situer plus près du point 75% que du point 25%. Dans notre cas, on observe l'inverse et le point 50% et plus proche du point 25%. En fait la variation du volume échantillonné est limitée à partir de distances de l'ordre de 100 à 300 mètres du bateau, car le bord inférieur du faisceau sonar atteint le fond. Cette situation se produit dans la zone de distribution des sardines qui vivent sur des petits fonds (15-60 mètres). Il semble donc que cette source de biais liée à l'augmentation du volume échantillonné avec la distance ne soit pas dominante dans le cas de la sardine, et que les variations de détection des bancs en fonction de leur éloignement et de leur pouvoir de réflection soient prépondérantes. Ceci permet d'expliquer que le point 50% soit plus proche du point 25%; en effet, plus on s'éloigne du bateau, et moins le nombre de bancs détectés est élevé.

La largeur et la position de la portée efficace sont variables d'une campagne à l'autre, selon les régions dans une même campagne, et en fonction de la taille et de la densité des bancs.

4.1.3 Détermination du poids moyen des bancs

Une enquête auprés des pêcheurs a permis d'obtenir la capture moyenne par calée et de determiner des poids moyens de bancs dans les zones d'activité de la flottille marocaine. Les données des bateaux de la pêcherie d'Agadir, ont conduit à une estimation du poids moyen d'un banc de 3,6 tonnes (moyenne établie sur les calées de 94 bateaux). On considère que dans la pêcherie d'Agadir, l'effort de pêche et la disponibilité des bancs de poissons sont tels que tous les bancs petits ou gros, sont capturés, et que ce chiffre est représentatif du poids moyen d'un banc dans cette région.

Pour la pêcherie de Tan-Tan (comm.pers.BELVEZE 1982) où les bancs observés sont plus gros, la capture moyenne par calée (306 observations), est de 22 tonnes, mais sachant que les professionnels ont tendance à éviter de pêcher les petits bancs, le poids moyen d'un banc est certainement surestimé. En outre, la distribution du poids par calée en fonction du nombre de calées ne suit pas une loi normale, car on observe une nette dominante des calées de faible tonnage. En conséquence la valeur modale de 12,5 tonnes par calée a été retenue comme plus proche du poids moyen réel.

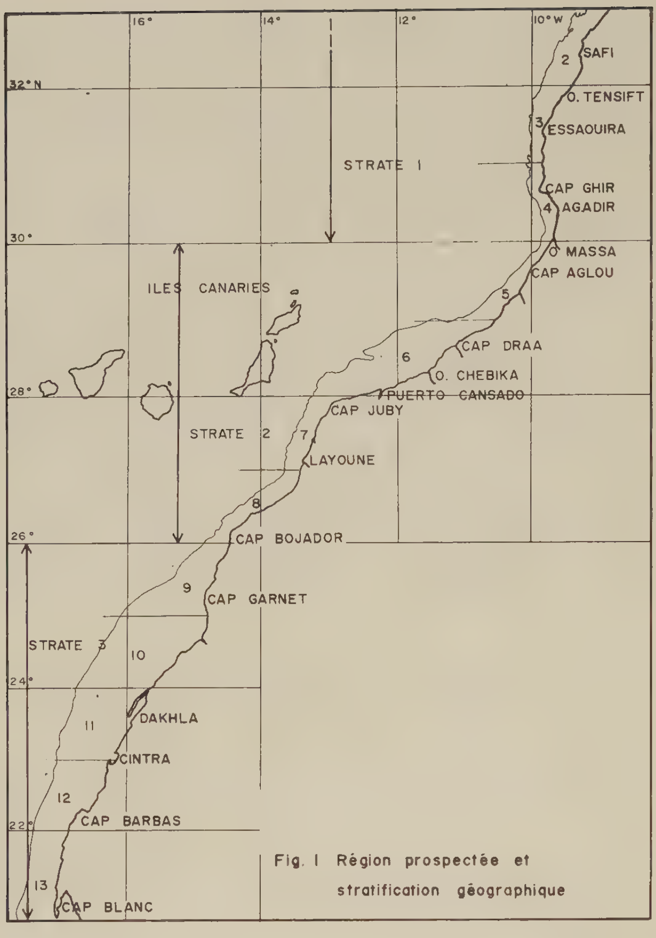

Fig. 1. Region prospectée et stratification géographique

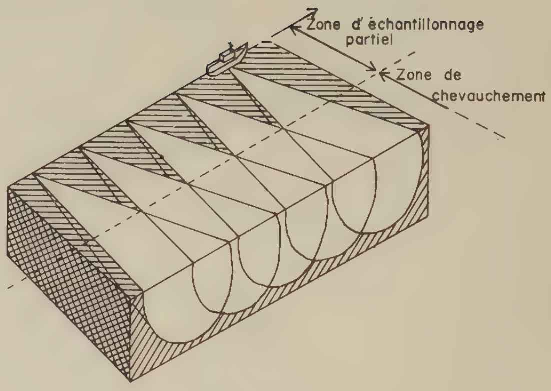

Fig. 2. Volume d'eau échantillonné par le sonar

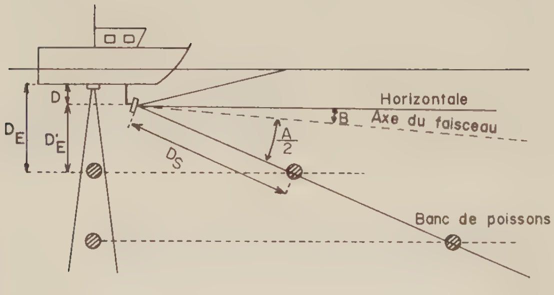

Fig. 3. Mesure de l'angle d'ouverture verticale du faisceau

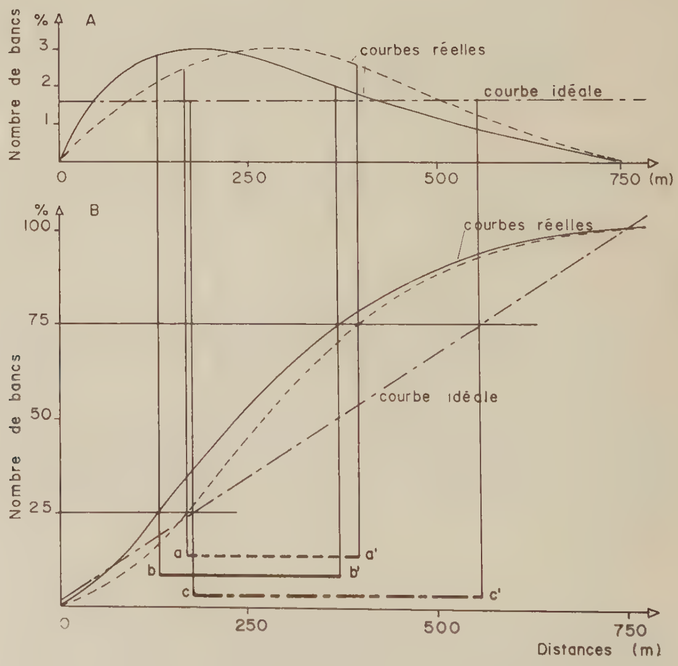

Fig. 4. Distribution idéale et réelle du pourcentage cumulé (B) de bancs en fonction de la distance. aa', bb', cc': portées efficoces

On a pu observer que la taille des bancs varie d'une région à l'autre et augmente notamment du nord vers le sud. En reprenant les examples de la Fig. 5 qui correspondent aux trois strates géographiques (Fig. 1), on note que les courbes sont décalées les unes par rapport aux autres. Ce décalage est dû à des différences dans la taille des bancs. En effet, plus les bancs sont de petite taille moins ils sont détectés loin du navire. Le pourcentage cumulé du nombre de bancs croit plus rapidement lorsque ces bancs sont petits. Dans la courbe n°1 située à gauche du graphique (Fig. 5) et qui correspond à la zone nord, les bancs sont d'une taille moyenne plus petite que ceux de la courbe de droite n°3, qui correspond à la zone sud.

La valeur de poids de banc de 3,6 tonnes obtenue à partir de la pêcherie d'Agadir est utilisée pour la strate 1, celle de 12,5 tonnes obtenue à partir de la pêcherie de Tan-Tan est utilisée pour la strate 2. Cette même valeur est aussi utilisée pour la strate 3 car bien qu'elle constitue probablement une sous estimation de la valeur réelle, le manque d'informations dans cette zone ne permet pas d'estimer une valeur plus appropriée.

4.1.4 Calcul de la biomasse détectée par le sonar

Pour chaque mille parcouru, on calcule d'abord le nombre de bancs par mille carré, Il est égal au rapport du nombre de bancs contenus dans la portée efficace sur la surface échantillonnée.

$$N = \frac{n}{le\ L_u}$$

où N = nombre de bancs par mille carré
n = nombre de bancs comptés dans la portée efficace
le = largeur de la portée efficace en mètres
L_u = longueur de l'unité d'échantillonnage en mètres.

Les données obtenues sont stratifiées par regroupement en intervalles de un degré de latitude (Fig. 1) et par tranches de profondeur: 0-20 m, 20-50 m, 50-75 m, 75-100 m, 100-200 m. Une valeur moyenne du nombre de bancs par mille carré est calculée pour chaque strate, à partir des données de jour seulement.

Connaissant le poids moyen des bancs et la surface de chaque strate, on calcule la biomasse par strate.

$$B_{Si} = A_i\ N_i\ d$$

où B_{Si} = Biomasse dans la strate "i" en tonnes.

A_i = Surface de la strate "i" en mille carré.

N_i = Nombre moyen de bancs par mille carré.

d = Poids moyen d'un banc en tonnes.

La biomasse totale est obtenue en faisant la somme des biomasses de chaque strate.

4.2 Biomasse détectée par le sondeur vertical et l'échointégrateur

Le même système de stratification par intervalle de un degré de latitude et strates de profondeur est utilisé. Dans chaque strate on calcule la déflection moyenne de l'échointégrateur sur la base des données de jour seulement, ceci pour pouvoir les combiner par la suite avec les donnés du sonar.

Plusieurs opérations de calibration de Sardina pilchardus ont été réalisées avec des poissons vivants (Burczynski et al ., 1982). La valeur obtenue pour le pouvoir de réflection est: TS = -32 dB/Kg (Sardina pilchardus 17,5 cm), un coefficient de transformation des données de l'échointégrateur a ensuite été calculé pour chaque campagne.

La biomasse dans chaque strate est donnée par l'expression:

$$B_{E_i} = A_i \times C \times \bar{M}_i$$

où B_{E_i} = Biomasse dans la strate "i" en tonnes.

A_i = Surface de la strate "i" en mille carré.

C = Coefficient de calibration de l'intégrateur en tonnes /M2/mm ref.1 mille.

$\bar{M}_i$ = lecture moyenne de l'intégrateur en mm.

La biomasse totale est obtenue en faisant la somme des biomasses dans cheque strate.

4.3 Combinaison des estimations du sondeur vertical et du sonar

La somme des biomasses estimées à partir du sonar et du sondeur vertical conduirait à une surestimation car les zones échantillonnées par les deux appareils se recouvrent, et une partie de la biomasse serait comptabilisée deux fois. Pour éviter cet inconvénient, les données ont été traitées comme suit:

On considère que les bancs comptabilisés dans la portée efficace du sonar constituent un bon échantillonnage de la tranche d'eau se situant entre la surface et la profondeur correspondant au centre de la portée efficace (Fig. 7). La biomasse B_S, calculée à partir de ces données correspond donc à la quantité de poissons se situant dans cette tranche d'eau. La distribution verticale des concentrations se sardines detectées au sondeur permet de déterminer le pourcentage de la biomasse B_E mesurée au desous de la zone couverte par le sonar. La biomasse totale B_T est obtenue en faisant la somme de la biomasse B_S de surface détectée par le sonar, et de la fraction de biomasse sous-jacente B_E détectée au sondeur vertical.

$$B_T = B_S + B_E$$

Seule les données obtenues de jour sont utilisées.

La position et la largeur de la bande efficace variant avec la taille des bancs, l'épaisseur de la couche d'eau couverte par le sonar n'est pas constante. Pour tenir compte de cet effet, les biomasses ont été combinées strate par strate. Dans le cas de la sardine, lorsque les bancs sont de grande taille, et que les concentrations se situent en eau peu profonde, la quasi-totalité de la biomasse est détectée au sonar.

5. RESULTATS

La méthode décrite ci-dessus a été utilisée pour déterminer la biomasse de sardines (Sardina pilchardus) lors de quatre prospections acoustiques effectuées en Novembre 1979, Juillet et Novembre 1980 et Octobre 1981.

Les résultats présentés au tableau Fig. 8 illustrent cette méthodologie. La biomasse absolue estimée est un ordre de grandeur, car les données sur le poids moyen des bancs devront être révisées dès que des élements nouveaux le permettront. Les estimations sont données par strates géographiques (Fig. 1).

Les chiffres du tableau 2 n'ont pas été corrigés pour tenir compte des problèmes de couverture géographique. En particulier, la zone comprise entre la côte et l'isobathe 20 mètres est généralement prospectée de facon imparfaite. De plus en Octobre 1981, la prospection n'a pas couvert la zone à moins de 4 milles de la côte pendant la journée dans la strate 3.

Les 1,7 millions de tonnes obtenus en Juillet 1980 sont certainement sous estimés, en effet, la prospection dans la strate 3, au sud du cap Bojador, a correspondu avec une période de mauvais temps où les mouvements du bateau et l'état de la mer limitaient les performances du sonar. Le nombre de bancs comptabilisés dans cette zone est probablement bien en dessous du nombre réel.

En Novembre 1980, on remarque que la biomasse totale de 793.000 tonnes détectée par la sondeur vertical est élevée comparée aux trois autres campagnes. La répartition verticale des concentrations de sardines lors de cette prospection était plus profonde que lors des autres campagnes.

La strate 1, qui correspond à la zone d'activité traditionnelle des sardiniers marocains présente toujours une faible abondance comparée aux autres strates. L'abondance dans cette région est la résultante du prélèvement opéré par la flottille marocaine, et de la biomasse de sardines qui a migré à partir de la strate 2. Dans cette dernière, l'abondance la plus forte enregistrée en Novembre 1980 correspond probablement à une immigration de sardine à partir de la strate 3. Bien que l'estimation dans la strate 3, soit certainement sous estimée, on note une diminution de l'abondance dans celle-ci, que l'on pourrait attribuer à un trés fort prélèvement de la part de flottes étrangères, ou à une remontée du stock de sardines vers le nord.

6. DISCUSSIONS ET CONCLUSIONS

La biomasse de la sardine atlantique marocaine *Sardina pilchardus*. A été estimée au cours de quatre campagnes de prospection acoustique de Novembre 1979 à Octobre 1981. La méthode d'élaboration des résultats est basée sur la combinaison d'une estimation de la biomasse des couches de surface au moyen du sonar, et de l'estimation de la biomasse des couches plus profondes au moyen du sondeur vertical relié à l'échointégrateur. Le nombre de bancs par unité de surface, détectés par le sonar est calculé sur la base des bancs compris dans la "portée efficace", zone pour laquelle on considère que les données sont de moins biaisées.

Des chiffres de poids moyen des bancs calculés à partir des rendements par calées ont été utilisés: 3,6 tonnes pour la région au nord de 30°N, correspondant à la zone d'activité traditionnelle de la pêcherie marocaine, et 12,5 tonnes au sud de 30°N.

Les estimations de biomasse de sardine déterminées sur ces bases n'ont pas été corrigées pour tenir compte de la couverture incomplète des régions peu profondes s'étendant de la cote jusqu'aux fonds de 15-20 mètres. Elles sont de 4,5 millions de tonnes en Novembre 1979, 1,7 millions de tonnes en Juillet 1980, 3,9 millions de tonnes en Novembre 1980 et 1,5 millions de tonnes en Octobre 1981. Les chiffres précedemment calculés pour Novembre 1979 (Bazigos *et al*., 1980), étaient de 2,4 et 1,6 millions de tonnes selon que l'on utilisait 3,2 ou 5 tonnes pour le poids moyen d'un banc. En Juillet 1980, les estimations étaient de 1 et 1,5 millions de tonnes pour les mêmes poids moyens de bancs (Lamboeuf *et al*., 1980).

Les différences entre ces chiffres sont liées à la valeur utilisée pour le poids moyen d'un banc; on peut ainsi voir l'importance de ce paramètre dans le calcul des estimations de biomasses basées en grande partie sur les données du sonar. De plus les premières estimations de novembre 1979 et Juillet 1980 ont été calculées en tenant compte d'un angle d'ouverture verticale du sonar de 10°, alors que les dernières estimations tiennent compte d'un angle de 21° le faisceau étant incliné de 2° dans les deux cas. Lors de ces premiéres estimations, la partie de la biomasse détectée par le sondeur vertical (20%) était plus importante, car la zone couverte par le sonar s'étendait moins en profondeur, en liaison avec l'angle d'ouverture verticale plus faible qui avait été retenu.

En valeur relative et compte tenu de la sous estimation de la biomasse de Juillet 1980 liée au mauvais temps qui a perturbé les performances du sonar, on note une diminution de l'abondance de Novembre 1979 à Octobre 1981.

On remarque que dans les estimations présentées ici, la quasi totalité de la biomasse de la sardine a été calculée à l'aide des données du sonar. Compte tenu de

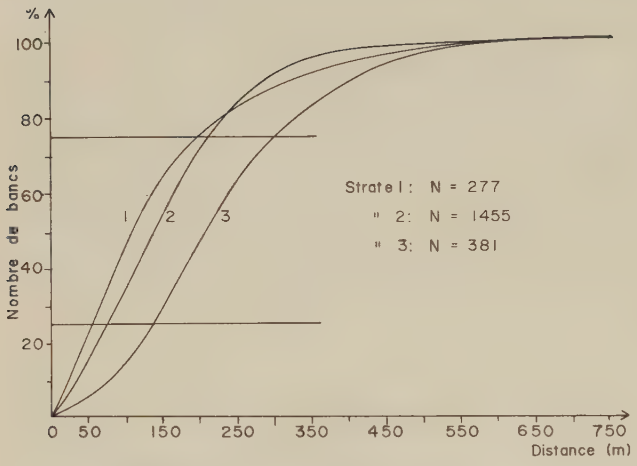

Fig. 5. Exemples de distribution en pourcentages cumulés du nombre de la distance. Novembre 1980

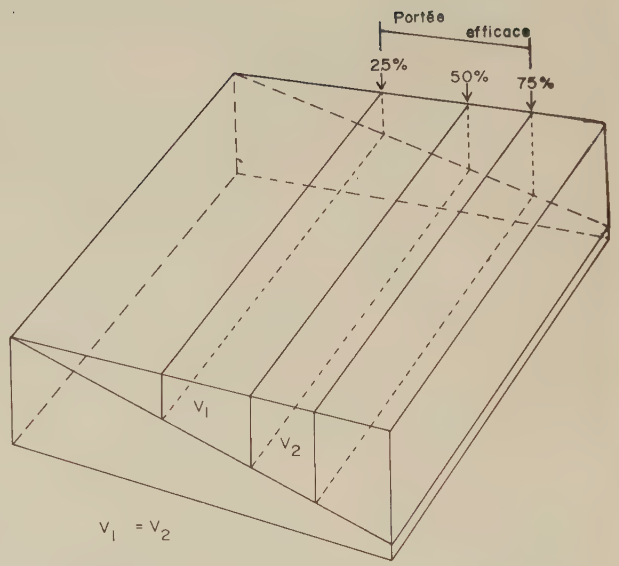

Fig. 6. Portée efficace du sonar et volumes d'eau échantillonnés correspondant aux seuils de 25, 50, et 75% de bancs détectés

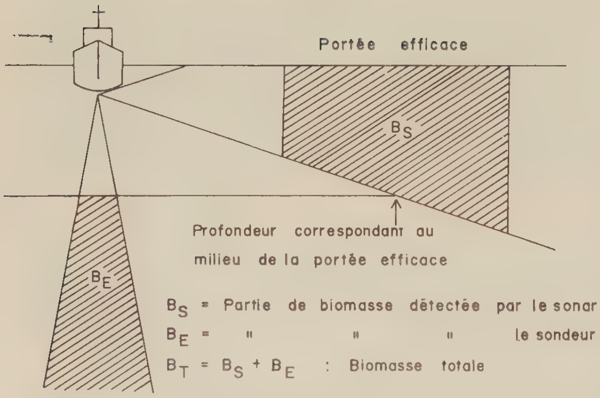
Portée efficace
B_S
B_E
Profondeur correspondant au milieu de la portée efficace
B_S = Partie de biomasse détectée par le sonar
B_E = " " " le sondeur
$B_T = B_S + B_E$: Biomasse totale

Fig. 7. Représentation schématique de l'estimation de la biomasse à partir des données du sonar et du sondeur

Date	Strate	Biomasse totale sondeur (jour)	Composante biomasse sondeur B_E	Nbr.total de bancs au sonar	Poids moyen d'un banc (tonnes)	Composante biomasse sonar B_S	Biomasse totale $B_T = B_E + B_S$
Novembre 1979	2	49 000	4 000	182 132	12,5	2 276 600	2 280 600
	3	89 900	7 500	178 053	12,5	2 225 600	2 233 100
	Total	138 900	11 500	360 185	-	4 502 200	4 513 700
Juillet 1980	1	9 200	0	3 245	3,6	11 700	11 700
	2	61 100	17 900	64 947	12,5	811 800	829 700
	3	302 900	0	70 239	12,5	878 000	878 000
	Total	373 200	17 900	138 431	-	1 701 500	1 719 400
Novembre 1980	1	23 800	5 200	20 642	3,6	74 300	79 500
	2	705 400	102 600	235 844	12,5	2 948 100	3 050 700
	3	64 000	0	65 712	12,5	821 400	821 400
	Total	793 200	107 800	322 198	-	3 843 800	3 951 600
Octobre 1981	1	9 600	0	4 031	3,6	14 500	14 500
	2	140 900	6 400	80 166	12,5	1 002 100	1 008 500
	3	29 800	0	41 961	12,5	524 500	524 500
	Total	180 400	6 400	126 156	-	1 541 100	1 547 500

Fig. 8. Biomasse de la sardine (Sardina pilchardus) au large des côtes marocaines en tonnes

l'angle d'ouverture verticale du faisceau, et de la distribution bathymétrique des sardines qui vivent en deçà des fonds de 60 mètres, le volume échantillonné par le sonar est limité vers le bas par la présence du fond. Dans ces conditions le sonar couvre toute la colonne d'eau et, les données fournies par le sondeur vertical sont moins prépondérantes.

Cette méthode de combinaison d'estimations faites au moyen du sonar avec celles réalisées au moyen du sondeur couplé à l'échointegrateur, a été mise au point pour répondre aux problèmes particuliers que pose l'estimation de la biomasse du stock de sardine dans les eaux marocaines. Elle peut être utilisée dans le cas d'autres stocks de poissons pélagiques vivant près de la surface.

ACOUSTIC ABUNDANCE ESTIMATION OF THE ICELANDIC STOCK OF CAPELIN 1978 - 1982

by

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ABSTRACT

During the period October 1978 - February 1982 several abundance estimates and year classes composition of the Icelandic capelin stock were obtained by acoustic methods. Surveying has been carried out in July-August, September, October, November as well as in January-February and on one occasion in early March. It has been found that consistent abundance estimates of the older year classes (excluding 0- and 1-group fish) can be obtained in autumn and winter by this method while the fish still occupy deep water areas off NW-, N-, and E-Iceland. Due to drift ice and periods of bad weather it has at times proved necessary to wait and repeat surveys. This paper describes and discusses the abundance estimates obtained during the above period, which have been used for management purposes.

RESUME

Durant la période octobre 1978 - février 1982, plusieurs estimations sur les quantitiés et l'âge des réserves de capelan islandais ont été obtenues par des méthodes acoustiques. Les évaluations ont été réalisées en juillet-août, septembre, octobre, novembre, en janvier-février, ainsi qu'une seule et unique fois en mars. Il s'est révélé que les évaluations quantitatives des espèces les plus âgées (à l'exception des poissons des groupes 0 et 1) pouvaient être obtenues en automne et en hiver grâce à cette méthode, alors que le poisson occupe les eaux profondes des zones N-O, N, N-E et E de l'Islande.

Il a été parfois nécessaire de repousser ou de répéter certains contrôles, à cause de déplacement des glaces flottantes ou du mauvais temps. Cette étude décrit et discute les estimations quantitatives obtenues durant la période nommée plus haut. Elles ont éte utilisées à des fins pratiques de régulation des réserves.

1. INTRODUCTION

The migration and behaviour of this stock have been studied by acoustic methods since the sixties. The catches of capelin show a rapid increase since 1964 (Table 1), and with this increase the need for accurate assessment of this stock soon became of paramount importance for management purposes. Since 1978 the abundance of this stock has been estimated by acoustic methods, and the aim of this paper has been to describe the results of the acoustic abundance estimates.

2. MATERIAL AND METHODS

The basic integration technique is described in Nakken and Dommasnes (1975). The surveyed area was divided into subareas, the integrated echo intensity for each subarea was converted to number of fish N using the equation:

$$N = C \times M \times A$$

Table 1. The total annual catch from the Icelandic capelin stock 1964-1980 (tons x 10^{-3}).

	Winter season		Summer and autumn season			
Year	Iceland	Faroes	Iceland	Norway	Faroes and EEC	Total
1964	8.6					8.6
65	49.7					49.7
66	124.5					124.5
67	97.2					97.2
68	78.1					78.1
69	107.6					107.6
1970	190.8					190.8
71	182.9					182.9
72	276.5					276.5
73	440.9					440.9
74	461.9					461.9
75	457.6		3.1			460.7
76	338.7		114.4			453.1
77	549.2	25.0	259.7			833.9
78	468.4	38.4	497.5	154.1		1 158.4
79	521.7	17.5	441.9	126.0	2.5	1 109.6
1980	392.0		367.2	118.6	38.7	916.5
81	156.0		484.6	91.4	37.0	769.0

Table 2. List of cruises.

Cruise no.	Date	Research vessel(s)
1	16-30 October 1978	RV "Bjarni Sæmundsson"
2	1-9 February 1979	RV "Bjarni Sæmundsson"
3	14 February-1 March 1979	RV "Bjarni Sæmundsson"
4	26 July-12 August 1979	RV "Bjarni Sæmundsson" RV "G.O.Sars"
5	25 September-5 October 1979	RV "Bjarni Sæmundsson" RV "Michael Sars"
6	14-26 October 1979	RV "Bjarni Sæmundsson"
7	4-30 January 1980	RV "Bjarni Sæmundsson"
8	11-22 October 1980	RV "Bjarni Sæmundsson" RV "G.O.Sars"
9	5-29 January 1981	RV "Bjarni Sæmundsson" RV "Arni Fridriksson"
10	5-16 February 1981	RV "Bjarni Sæmundsson"
11	14-23 October 1981	RV "Bjarni Sæmundsson" RV "G.O.Sars"
12	3-13 November 1981	RV "Bjarni Sæmundsson"
13	26-30 November 1981	RV "Bjarni Sæmundsson"
14	11-22 January 1982	RV "Bjarni Sæmundsson" RV "Arni Fridriksson"
15	27 January-21 February 1982	RV "Bjarni Sæmundsson"

Where C is the conversion factor. The value of this factor was set to $8.1 \times 10^6 \cdot l^{-1.91}$ (l = fish length in cm). This value had previously been established for the instrumentation of the Norwegian research vessel "G.O.Sars" (Dommasnes and Røttingen 1977), and used in the abundance surveys for the Barents Sea capelin.

M is the mean integrated echo intensity of the relevant subarea. Since the conversion factor is established for the instrumentation of "G.O.Sars", the M-values from the other vessels were converted to "G.O.Sars"-values. This has been done in two different ways:

1. Calibration with a standard reference target (Foote et al., 1981) simulating echo intensity over 1 nautical mile.
2. Inter ship calibration on a scattering layer of mostly 0-group capelin and plankton (Røttingen, 1978).

Initially during the RV "Bjarni Sæmundsson" surveys in October 1978 and February-March 1979, a slightly different technique of data evaluation as well as C values were used (Vilhjálmsson and Reynisson, 1979). After intercalibrations with RV "G.O.Sars" in August 1979 it was, however, possible to recalculate the previous survey results.

The performance of the acoustic instrumentation of the vessels employed has always been remarkably consistent. Thus, there has on all occasions been high correlation between echo integrator outputs during intercalibrations (r = 0.97-0.99).

In the surveys the 0-group capelin is grossly under-represented as compared to older year classes. To some extent this also holds true for I group fish. Therefore, the contribution by 0- and I-group capelin to the echo abundance has been subtracted and the estimates of stock biomass presented thus approximately represent the adult or maturing stock.

A is the subarea measured in square nautical miles.

3. RESULTS

The surveys are summarized in Table 2, and the obtained stock estimated are given in Table 3.

Cruise 1, October 1978:

During the short period 20-29 October the 1978 capelin spawning stock was surveyed 3 times and acoustic abundance estimates obtained. This was possible because through previous scouting by research and fishing vessels it had been established that practically all the mature capelin were assembled in a very limited area in Denmark Strait off Northwest Iceland. Weather and ice conditions were good for a short spell of bad weather which produced an underestimate in the second survey.

Cruise 2 and 3, February-March 1979:

During this period the spawning stock proved to be divided in two almost equal halves, one being located off East and Northeast Iceland and the other off Northwest Iceland (Figs. 1 and 2).

In the first week of February the eastern component was successfully surveyed 3 times with similar results. A survey of the western component followed immediately afterwards and was repeated in the 3rd week of February.

In both instances considerable time was spent in waiting for suitable weather which then prevailed for the duration of the actual abundance estimates.

A fourth survey of the eastern component was carried out in shallow waters at the SE-coast of Iceland on 27/2 - 1/3. This survey took place at night and was possible only because at that time of the day the capelin formed a more or less continuous pelagic scattering layer away from the bottom. Counting the catch and natural mortality the winter survey results are in fairly good agreement with findings in the autumn before.

Table 3. Echo stock by number and weight by year classes ($N \times 10^{-9}$, $W \times 10^{-3}$ tonnes), October 1978 - January 1982.

Yearclass	1975		1976		1977		1978		1979		Total	
Date	N	W	N	W	N	W	N	W	N	W	N	W
Oct 1978, I	20	584	50	944							70	1528
" II	(16	427	39	735							55	1162)
" III	23	603	55	1036							78	1639
Average	22	576	53	990							75	1566
Feb 1979 I	3	78	23	457							26	535
E-comp. II	3	80	24	473							28	553
" III	3	85	26	506							29	591
Average	3	80	24	479							27	559
Feb 1979 I	5	107	28	495							33	602
NW-comp. II	6	132	24	411							40	543
Average	5	120	26	453							31	573
Total	8	200	50	932							58	1132
Feb-Mar 1979 E-comp.	4	93	13	249							17	342
July-Aug 1979	+	1	5	86	33	390					39	477
Sept-Oct 1979	+	4	8	166	42	639					50	808
Oct 1979	+	8	9	209	50	780					59	998
Jan 1980			4	92	42	664					46	758
Oct 1980			5	128	19	378					24	506
Jan 1981					3	87	11	235			14	322
Oct 1981							+	4	7	135	7	139
Nov 1981 I							+	8	18	335	18	342
" " II							1	18	18	328	21	388
Average							+	13	18	332	20	365
Jan 1982							+	13	8	154	9	167
Feb 1982							+	1	1	20	1	21
Total							+	14	9	174	10	188

Cruise 4, July-August 1979:

During this joint survey capelin were mainly recorded in the frontal zone of the East Greenland current from 66°N to 72°N the main concentrations being north of Cape Horn and west of Jan Mayen.

There clearly was considerable schooling in the surface layers above transducer range and much drift ice was observed in the Strait between Northwest Iceland and

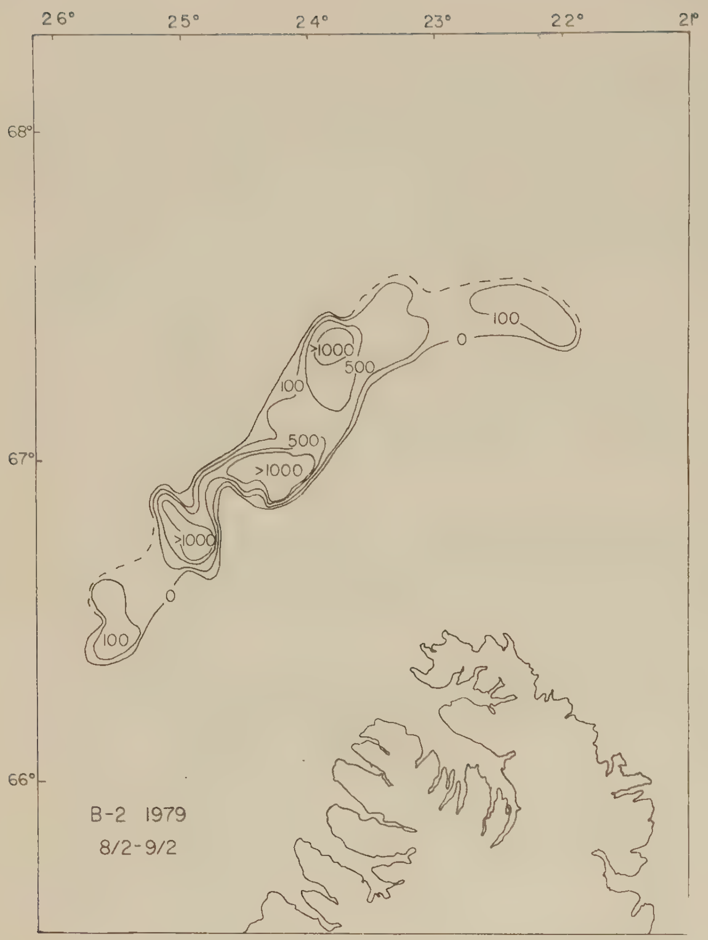

Fig. 1. Distribution of echo abundance of capelin. NW-Iceland, 8-9 February 1979.

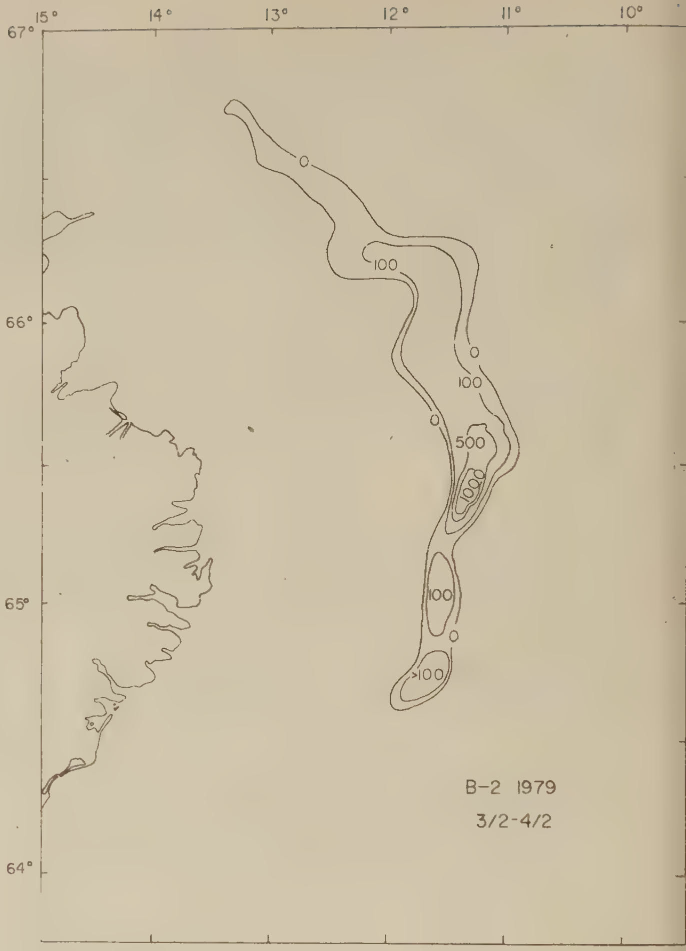

Fig. 2. Distribution of echo abundance of capelin. E-Iceland, 3-4 February 1979.

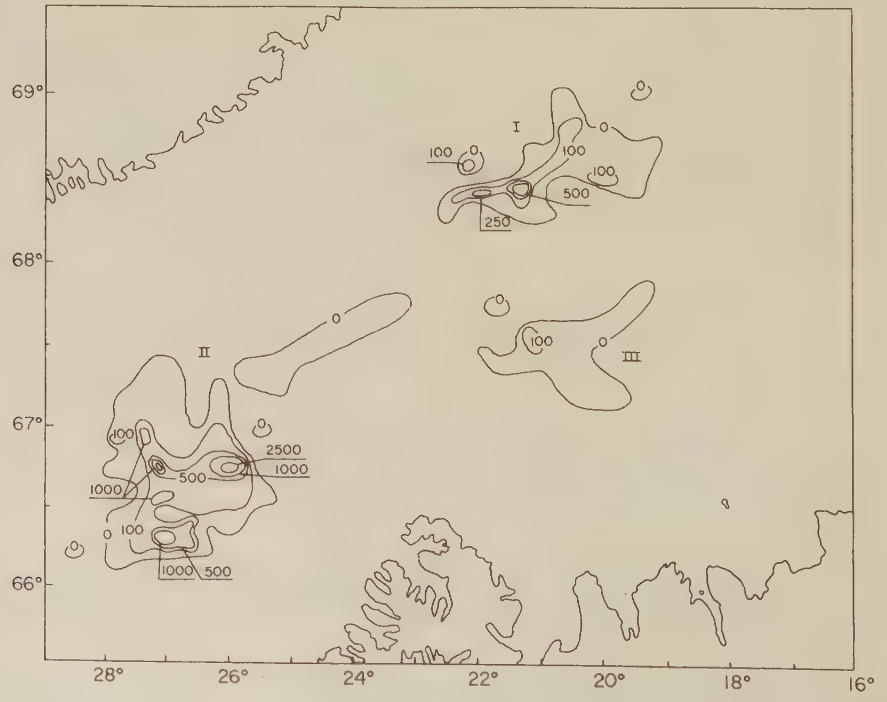

Fig. 3. Distribution of echo abundance of capelin. NW-Iceland, 11-22 October 1980.

Greenland. Both these factors rendered parts of the stock inaccessible and the abundance estimate was, therefore, regarded as an underestimate of unknown magnitude.

In addition an attempt was made to survey the stock in September. There was even a more pronounced surface schooling than in August and the experiment failed.

Cruise 5 and 6, September-October 1979:

During the period 25/9 - 5/10 Iceland and Norway carried out a joint survey of the capelin stock east of 28°W. This survey was thought to have covered practically all of its distribution area with the possible exception of the extreme northern region where coverage was insufficient because of bad weather. Otherwise weather and drift ice did not interfere with survey work and shoaling in the surface layers did not seem particularly pronounced.

The maturing stock component was resurveyed in the period 14-28/10 in order to check on previous findings which had been strongly contested by local fishermen and authorities. In both surveys most of the stock was registered in deep waters off the western and central north coast of Iceland.

Counting the catch in the intervening period the new estimate differed considerably from the previous one being higher by amount 250 000 tonnes. In retrospect the most plausible explanation seems to lie in survey tracks being to sparsely spaced in areas of very dense concentrations during the joint survey.

Cruise 7, January 1980:

The 1980 spawning stock had a most unusual distribution during this survey. Thus, all the capelin were then located at or near the shelf edge off the northwest peninsula of Iceland or about 200 n.m. further west than usual at this time of the year.

At the outset the capelin area was covered by drift ice, which after 20 January receeded enough to render the fish accessible. An acoustic abundance estimate was then obtained during 25-28 January under highly satisfactory conditions regarding weather, ice and fish behaviour. The resulting abundance estimate was significantly higher than that from late October in the year before. This was not totally unexpected considering the somewhat inadequate coverage of the northernmost part of the distribution area during that survey.

Cruise 8, October 1980:

This time the main concentrations were recorded in the Denmark Strait off the northwest peninsula of Iceland. Lesser concentrations of capelin were also recorded at approximately 67°30'N and 68°30'N between 19° and 22°W (Fig. 3). Apart from minor interference by drift ice survey conditions were good.

Cruise 9 and 10, January 1981:

The capelin were recorded in a 5-15 n.m. wide area just off the shelf edge off Northeast Iceland. Their distribution was patchy, the capelin being registered as single shoals or aggregations of moderate density rather than a scattering layer.

Difficulties were encountered due to changing drift ice conditions in the northernmost part of the distribution area as well as the highly sporadic distribution of the fish. Three successive surveys of the spawning stock abundance were carried out. The capelin were recorded in a long but very narrow region just outside the shelf edge from E of Langanes northwestwards to nearly 18°W. Distribution was highly sporadic. Single shoals or aggregations of shoals alternated with areas of very low densities. The bulk of the migration, therefore, was assembled within a minor part of the total area of distribution. Under such circumstances it is highly doubtful of deviations, positive or negative, will even out as they do under more normal conditions unless the survey grid is very densely spaced. The best estimate probably is an average of all three surveys or about 350 000 tonnes which happens to be approximately the result of

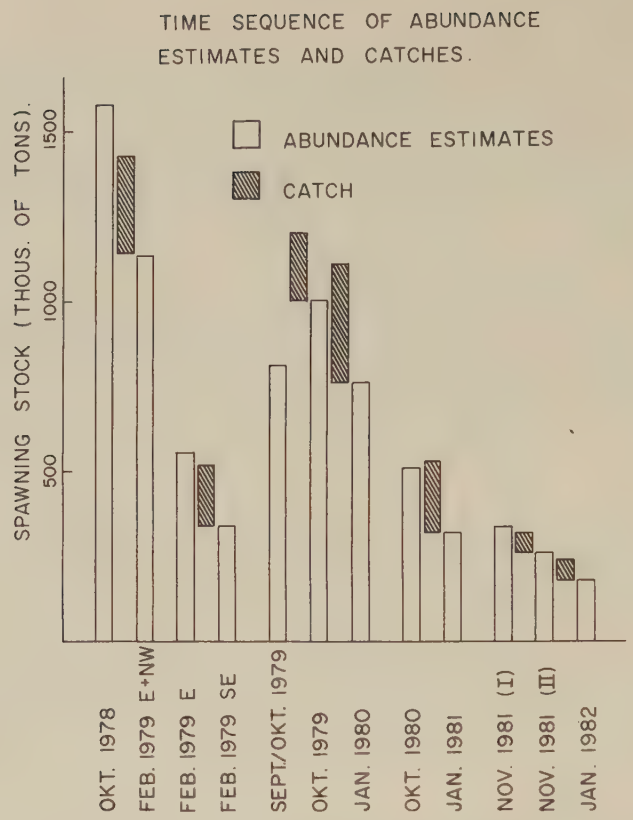

Fig. 4. Successive acoustic abundance estimates of the Icelandic capelin stock and the catch during the intervening periods. October 1978 - January 1982.

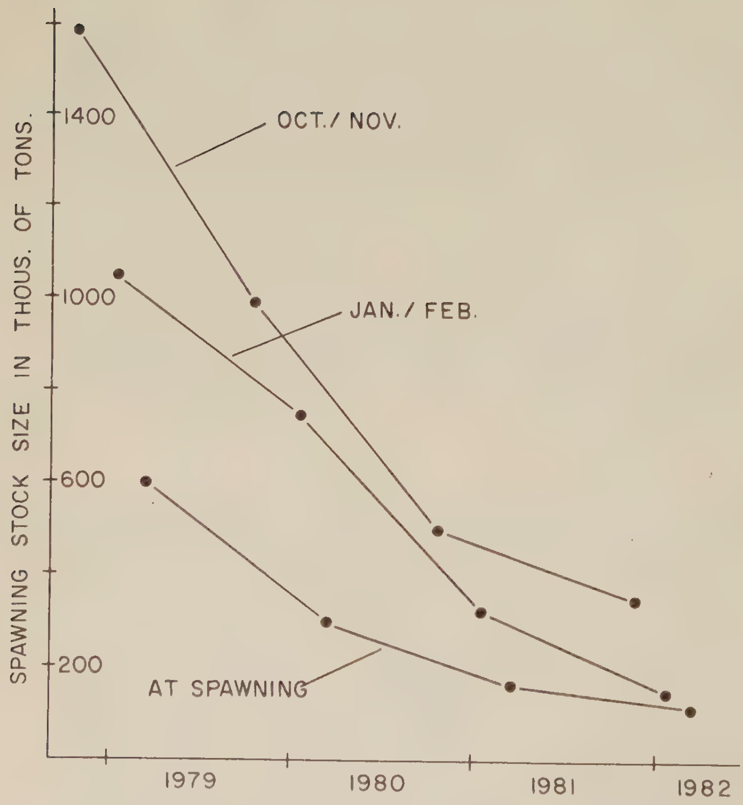

Fig. 5. Changes in the abundance of the 1979-1982 spawning stocks of the Icelandic capelin as estimated by the acoustic method.

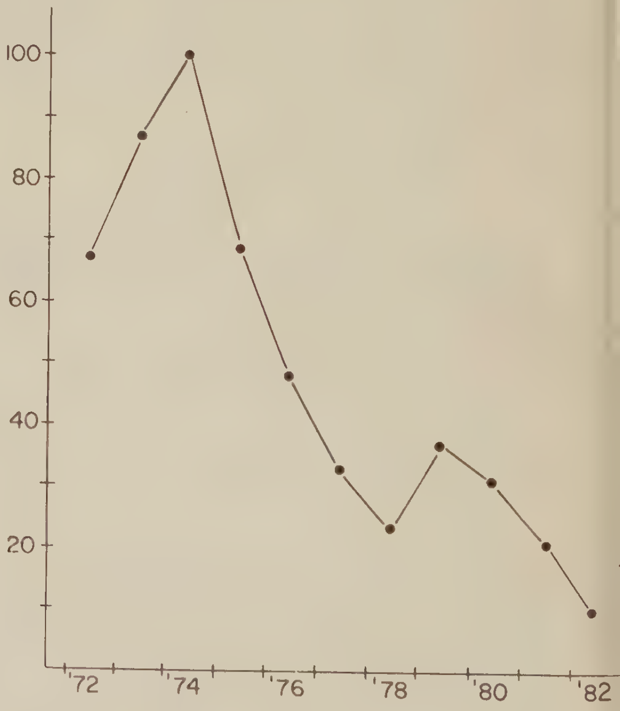

Fig. 6. 0-group indices. August 1972-1982.

the last survey when the grid was much denser than in the other two. Scouting did not reveal concentrations of mature capelin off N- or NE Iceland.

Cruise 11, 12 and 13, October-November 1981:

The northern component of the stock, which has its feeding grounds in the area W and NW of Jan Mayen, was during 14-23 October located between 69°N and 70°30'N. The main part of the adult stock was, however, located off N-Iceland, between 67°30' and 68°30'N.

Much drift ice was encountered in the Denmark Strait where the bulk of the stock was located in 1980. Although good weather prevailed through this joint survey it was concluded that, because of the extension of drift ice as well as the generally scattered distribution of the fish, the result might represent an underestimate of considerable magnitude.

During November 3-13 another survey of the 1982 spawning stock was carried out. The spawning stock had assembled off the central and eastern N-coast of Iceland. Survey conditions were excellent there being good weather and much less drift ice in the Denmark Strait, as well as more limited distribution than encountered in October. Counting the catch and natural mortality during the intervening period this abundance estimate of the adult stock was about 3 times higher than the pervious one.

A third survey was then carried out during the last days of November. The resulting abundance estimate was practically the same as obtained earlier in the month when the catch during the intervening period had been added.

Cruise 14 and 15, January-February 1982:

In January four consecutive surveys of the 1982 spawning stock were carried out off E-Iceland. The results of the first three judged inconclusive due to interference by rough weather and seas. During the fourth survey, however, weather and sea remained calm, the capelin being recorded as a continuous scattering layer which was highly convenient for acoustic abundance estimation.

In February a small amount of mature capelin was recorded off NE Iceland. These fish were not registered in January and must therefore, be added to that estimate. The total corresponds well with the November estimates from the year before when account has been taken of the catch as well as natural mortality. Practically no mature capelin was registered off N and NW Iceland in January-February 1982.

4. DISCUSSION

The Icelandic capelin has a short life span, the greater part of a year class spawn and die as 3 years old. Advice for management purposes has therefore to be based on direct observations of stock size.

Estimates of the adult capelin stock have been made since 1978 on the basis of acoustic investigations. However, when using this method, sources of error may be encountered due to the nature of the distribution area as well as variations in the behaviour and migration pattern of the species.

The feeding area of the capelin stock is wide. Apart from the shelf areas off North and Northwest Iceland 1-3 group capelin generally feed in the area Iceland-Greenland-Jan Mayen. Drift ice is a common phenomenon in the Denmark Strait in spring and summer, but has usually receded or sometimes almost vanished by autumn. During its highly variable migrations in the feeding period, which lasts from April to September-October, the stock may be distributed anywhere within the above mentioned waters depending on environmental conditions.

The plankton organisms, on which the capelin feed, are often located near the surface. The capelin will therefore be above the depth of the hull mounted transducer, this will result in an underestimation of the stock size.

The above mentioned factors are probably the main causes for the underestimates of stock size which have been obtained during the surveys carried out in the main feeding period (May-September).

The surveys carried out in autumn and winter yield more consistent estimates. During this period the maturing part of the Icelandic capelin stock has a relatively limited distribution in an area which is more or less free of other sound scatterers. Under such circumstances, repeated acoustic estimates of stock size can be carried out in a very short time for comparison. Exceptions are such cases when the capelin are late in returning from their feeding migrations and when atmospheric conditions cause a pile-up of drift ice over the East Greenland shelf and in the Iceland-Greenland channel south of Scoresby Sound. In such cases surveys carried out in the first three weeks of October have sometimes been inconclusive, and therefore repeated shortly afterwards.

Fig. 4 shows the abundance estimates together with the catch during the intervening period. No attempt has been made to estimate and incorporate losses by natural mortality. Estimates of abundance, which at the time were recognized as being obviously defective (September 1978, July-August 1979 and October 1981) have been omitted.

The estimates show a good correlation with the exception of those carried out in September-October 1979. At the time of the first estimate only part of the northern stock component had returned from its feeding grounds to the wintering area off North-Iceland. It may still have been feeding in the surface layers and also have been distributed too far north for the surveys to cover it properly. There is little doubt that the subsequent October 1981 survey yielded too low an estimate for the latter season. Furthermore, it is likely that in both instances cruise tracks were in certain areas too widely spaced considering the high density of the fish there.

The very limited distribution area of the adult capelin in late autumn and winter has, on several occasions, made it possible to survey the same stock component two or more times in a very short period of time (Table 2). In this way the reliability of the acoustic method of abundance estimation can be tested.

The abundance estimates of the Icelandic capelin stock obtained under adequate survey conditions seem to be reliable. Whether looked upon as indices or in absolute terms they, therefore, represent a correct picture of the development of the Icelandic capelin stock in the period which they cover. The alarming rate of decline in the abundance of mature component of this stock as well as the quantity that has been allowed to spawn are shown in Fig. 5. The decline also coincides with a decline in the comparative measurements of 0-group capelin which have been obtained in August annually since 1972 (Fig. 6). These indices have been calculated on the basis of the number of 0-group capelin in trawl catches.

From the data presented here it seems that, regarding the adult stock, surveying should not start earlier than October. On the other hand surveying will probably not succeed after the spawners have entered the shallow coastal waters at South and Southwest Iceland due to interference by bottom echoes as well as other biological scatterers.

HYDROACOUSTIC ASSESSMENT AND MANAGEMENT OF HERRING FISHERIES IN WASHINGTON AND SOUTHEASTERN ALASKA

by

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ABSTRACT

Acoustic surveys of Pacific herring populations in Washington and Southeastern Alaska have been conducted since 1971. The fisheries on herring are short-term (sometimes only hours) and very intense. These characteristics preclude the use of most traditional assessment techniques for management. The acoustic techniques have allowed assessment and management of the fisheries by quota on a daily basis in some cases. The post-season comparisons indicated very satisfactory accuracy and precision in most cases. However, in a few cases, anomolous results were observed, which might be due to undetected species, size changes or unusual behaviour patterns, and are the object of continuing research.

RESUME

Des ètudes acoustiques ont ete effectuées depuis 1971 sur les populations de hareng du Pacifique à Washington et au sud-est de l'Alaska. Les pêcheries de hareng sont de courte durée (parfois quelques heures) et très intensives. Ceci élimine l'utilisation de nombreuses techniques traditionnelles d'évaluation au fin d'aménagement. Les techniques acoustiques ont permis l'évaluation et l'aménagement des pêches par quote-part quotidienne dans certains cas. Des comparaisons effectuées après la saison des pêches ont indiqué une précision et une exactitude satisfaisantes dans la plupart des cas. Néanmoins, parfois, les résultats obtenus étaient anormaux en raison d'espèces non-détectées, de changement de taille ou de comportement peu commun et ces derniers font l'objet d'enquêtes continuelles.

1. INTRODUCTION

Fisheries for herring (Clupea harengus pallasi) on the west coast of the United States and Canada provide a challenge for fisheries management. The herring migrate from offshore waters during winter or spring, the timing varies among stocks, and spawn during spring in subtidal and intertidal areas. The major fisheries are for bait during winter and sac-roe during spring. Traditional methods of determining abundance or setting fish rates are inadequate, especially for the short duration sac-roe fisheries. Catch Per Unit Effort (CPUE), virtual population analysis/cohort analysis (VPA) or Yield Per Recruit (Y/R) provide only post-harvest information, often with lags of several years. Problems with effort standardization and harvesting of aggregated fish (CPUE), the need for independent estimates of highly variable recruitment (VPA), and sexual maturity being reached after maximum cohort biomass (Y/R) make these methods difficult to apply.

Historical fisheries for herring suffered as a result of these management difficulties and collapsed in the early 1960's as a result of overfishing. Subsequent management philosophy in the United States has been very conservative in order to prevent further overfishing. This philosophy combined with limited resource assessment

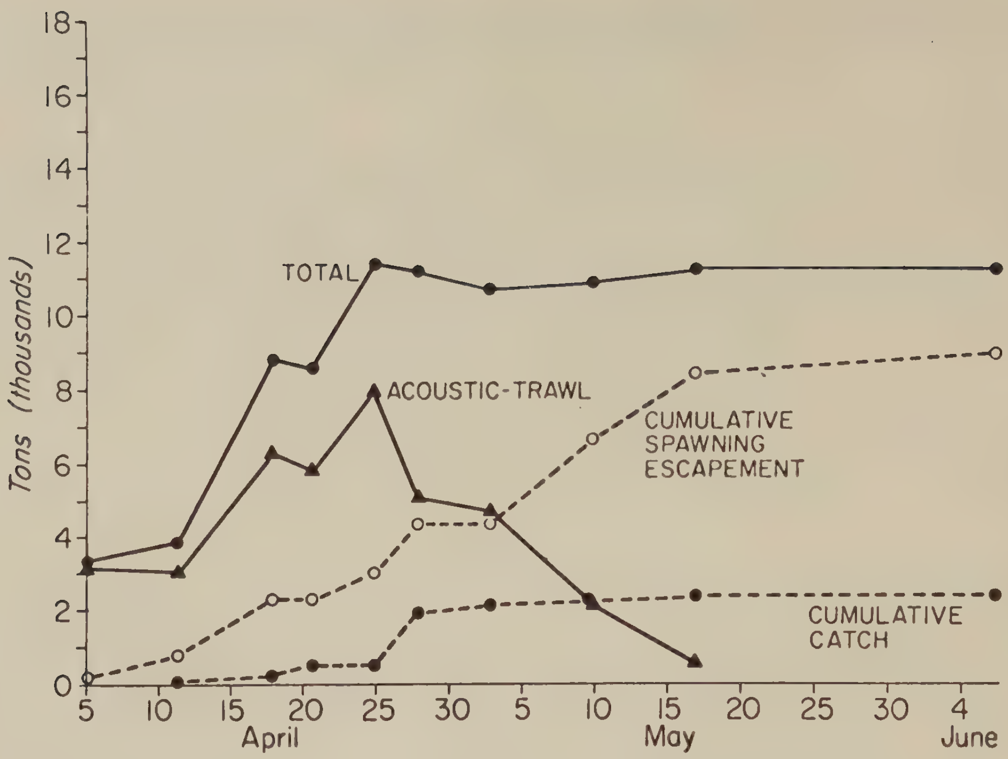

Fig. 1. Herring population estimates from acoustic-trawl surveys, spawning ground surveys, and catch records for the 1977 Strait of Georgia sac-roe fishery

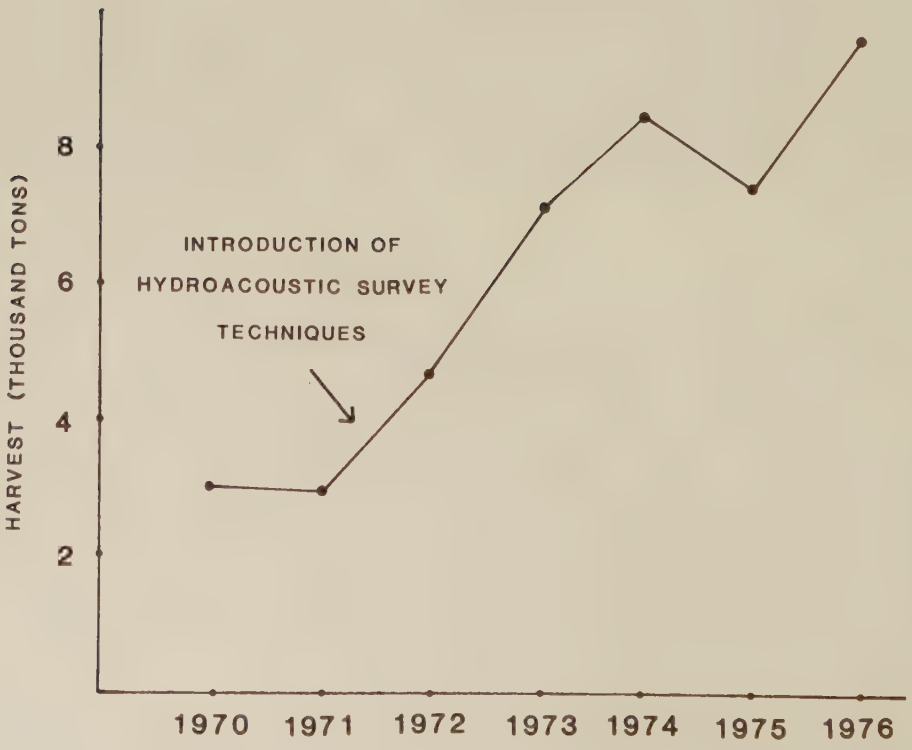

Fig. 2. Annual harvest of herring in Southeastern Alaska before and after introduction of hydroacoustic survey techniques

capabilities resulted in low harvests during the late 1960's. In 1971, the recently developed echo integration technique was applied in both the states of Washington and Alaska. The hydroacoustic technique greatly increased the stock assessment capability of the state management agencies and allowed for much more precise management. In southeastern Alaska this capability resulted in a four-fold increase in the allowed harvest in the next 5 years. In the successive 10 years, over 700 hydroacoustic surveys have been conducted in southern Alaska and a similar level of effort in Washington. This paper provides an overview of the methodology and general results of this effort.

2. MATERIALS AND METHODS

The general methodology of the hydroacoustic surveys for herring are described in Thorne (1977 and 1977a). The hydroacoustic data acquisition system for most of the surveys is based on a modified 105 kHz Ross 200A echosounder (Thorne et al., 1972). The hydroacoustic data from the echosounder are heterodyned to 5 kHz and recorded on analog magnetic tape for later analysis. In Alaska, five ships each with individual data acquisition systems conduct the surveys. Transducers are hull-mounted. A specially designed calibration system is used on these vessels. The system includes a calibrated standard hydrophone on a frame which is attached by a diver to a mounting plate behind the transducer. This allows complete system calibration and is usually done at least once per year for the vessels. The receiver gain characteristics are measured for every run by the use of an internal calibration signal in the hydroacoustic system.

In Washington, the data acquisition system is portable and used on various vessels. The transducer is usually suspended over the side at the end of a reinforced pipe. The data acquisition system is completely calibrated before and after each field season at the University of Washington Applied Physics Laboratory, as well as the receiver gain calibration before and after every run. For the past 3 years, a Biosonics 101 scientific echosounder has been used for the surveys in Washington.

Survey procedures vary among locations. In Washington, surveys are conducted primarily at night when the herring are more disperse in midwater. Standard survey tracks are followed. Uniform coverage is approximated by maintaining a ratio of 2 x 10^6 m^2 surface area per transect mile, or less in areas where heavy fish concentrations usually occur. The exception is the Strait of Georgia, where survey time restrictions (dusk to dawn) preclude sampling at a high intensity. The surveys in Washington are run from two vessels, hydroacoustic and trawler. The echo sounding is conducted first and provides a basis for establishing trawl stations and allocation of trawling effort. Acoustic transecting speed is approximately 8 knots.

In southeastern Alaska the procedure is to define an area encompassing a herring concentration by preliminary search or previous experience, then run a series of oblique transects spaced evenly over the area (Thorne, 1977a). In most cases these herring are segregated from other species so that net sampling is not required.

After the survey, the data tapes are analyzed in Seattle. The tapes from Alaskan surveys are sent either by mail or air express depending upon time limitations. Analysis is by echo integration using digital integration systems (Thorne, 1973, 1977a). The density estimates from the echo integration are based on an assumed acoustic target strength of -33 dB/kg in most cases. In the past three years adjustments have been made if the mean length of the fish is known to be less than 15 cm or greater than 30 cm.

3. RESULTS AND DISCUSSION

3.1 Washington

Four major herring congregation areas are currently recognized and surveyed on a regular basis: 1) southern Puget Sound; 2) northern Hood Canal and Protection Island; 3) greater Bellingham Bay and the San Juan Islands; and 4) the eastern portion of the Strait of Georgia. The latter area contains the most significant fishery and best

Table 1. Stock Assessment Summary, U.S. Strait of Georgia sac-roe herring, 1976-1979.

Year	Total catch	Total escapement	Catch + escapement	Average of full recruitment point estimates[1]
1976	2.190	9.590	11.780	12.700
1977	2.300	8.800	11.100	11.040
1978	2.120	8.840	10.960	12.700
1979	1.920	8.040	9.960	8.950

[1] This estimate consists of the average of acoustic-trawl plus cumulative escapement plus cumulative catch point estimates from the time of full recruitment through the final catch plus escapement estimate.

Table 2. Number of surveys and estimated herring biomass in three areas of Washington, 1975 to 1982.

	South Sound		Protection Island/ North Hood Canal		Bellingham Bay/ San Juan Islands	
Year	No. of surveys	Biomass (10^3 tons)	No. of surveys	Biomass (10^3 tons)	No. of surveys	Biomass (10^3 tons)
1975-76	6	17.2	2	12.5	0	--
1976-77	4	11.9	2	8.5	2	8.6
1977-78	3	6.2	1	7.5	1	3.0
1978-79	3	8.8	2	4.1	0	--
1979-80	4	4.2	2	7.0	1	1.8
1980-81	6	7.8	2	9.0	4	2.5
1981-82	4	9.0	3	4.5	7	6.0

Table 3. Commercial harvests and hydroacoustic estimates of herring abundance in Sitka Sound, 1976-1981.

Year	Commercial harvest (lbs x 10^6)	Hydroacoustic estimate (lbs x 10^6)
1976	1.6	14.6
1977	0	11.3
1978	0.4	29.6
1979	4.5	62.7
1980	8.8	79.0
1981	7.2	54.0

illustrates the application of hydroacoustics to the herring management in Washington. This stock is migratory and begins congregating in the eastern portion of the Strait in late March, where it matures and then spawns on adjacent beaches from April through May. The fish are commercially harvested for sac-roe by a relatively large fleet of purse seine and gill net vessels fishing on or near the spawning grounds. The fishery can be very short term. In 1977, 75% of the total quota was taken in one day. Strict management controls are required to protect the stock from overharvest. The present management plan requires a minimum 9,000 ton population of maturing herring before the fishery can open. A combination of hydroacoustic-trawling surveys, spawning ground surveys, and daily catch records are used to monitor the status of the fishery. During the initial stages of the immigration, the hydroacoustic-trawling surveys account for most of the herring biomass. After the fishery opens, declining hydroacoustic estimates are compensated by increases in the biomass accounted for in the catch and spawning ground surveys (Trumble, Thorne, and Lemberg, 1982). Fig. 1 illustrates the biomass values from these sources and the estimated total population during the 1977 fishery. Table 1 summarizes the results from 1976 to 1979 and shows the agreement between the biomass estimates during the fishery and the final catch and escapement numbers. In all years the preliminary estimates derived primarily from the hydroacoustic-trawl surveys have been in good agreement with the final values from the catch and escapement.

Seventy-seven hydroacoustic surveys of herring have been conducted in the other three areas of Washington in the past 10 years. Table 2 summarizes the results from the past 7 years.

3.2 Alaska

The number of surveys conducted in Alaska have varied from only 20 the first year (1971) to 141 surveys in 32 different areas in 1979. The herring populations are dynamic, and the very long coastline presents a major sampling problem. Substantial concentrations of fish are observed in several areas, including Anita Bay, Carrol Inlet, Bocas de Finas, Port Camden, Tenakee, and Lynn Canal. One of the largest concentrations is the spawning stock in the Sitka area. This fishery has recently expanded considerably as a result of successful recruitment. The results of annual acoustic estimates of this stock and commercial harvest from 1976 to 1981 are given in Table 3.

Despite the size and dynamic nature of the herring stocks in southeastern Alaska, several patterns have become apparent as a result of the consistent effort with well-calibrated equipment. Availability of the fish to detection by the acoustic gear, i.e., a midwater distribution, is a critical factor in the success of an acoustic survey and is greatly affected by diel changes in distribution. The herring migrate toward the surface and disperse with darkness. This behaviour reverses at dawn. In shallow water the fish may be too close to the bottom for detection. In Washington the herring seem to be confined to the midwater at night, but in Alaska the herring often migrate near surface and near shore at night and may also be undetectable. In these circumstances the best conditions for acoustic surveys are deep water where fish are off bottom during day or during dusk as fish move off bottom but before significant dispersal. In some shallow water areas in Alaska, reasonable estimates are not possible with the currently used acoustic techniques because of these behavioural characteristics.

Another distributional pattern which seems to produce anomalous results in Alaska is high density near surface schools during day. This situation often produces unreasonably high values. The most likely explanation is that the fish are not adult herring, but juvenile herring or other small schooled fishes which have different target strength characteristics.

As in the Strait of Georgia fishery, the seasonal migration patterns need to be taken into account in the survey design. Sometimes these patterns vary from year to year. For example, the stock which supports the large sac-roe fishery near Sitka left their overwintering grounds two months early in 1981 because of anomalously high water temperatures.

The extensive efforts in both states have included many replicate surveys which have allowed evaluation of the survey intensity required for any given management precision. The major component of variability is the degree of patchiness of the fish distribution (Thorne 1977 and 1977a). In addition, two-vessel synoptic surveys have been conducted in Alaska including a 14 survey effort in the Sitka area in 1979 which showed excellent agreement between the two vessels.

4. CONCLUSIONS

Although uncertainties are associated with the hydroacoustic results because of lack of information in the areas of target strength, species and size composition, and behaviour, the application of the techniques in a consistent fashion with carefully calibrated systems has reduced these uncertainties to within workable bounds. The procedures provide very satisfactory information for the current management philosophy in both states, which is to maintain populations at recent historical levels through a combination of biologically reasonable exploitation rates and minimum escapement levels. Further, the ability to obtain timely information on stock conditions has allowed increased harvests on the relatively unexploited Alaskan stocks because of reduced danger of overfishing. Consequently, commercial harvest of herring in Southeastern Alaska increased considerable following introduction of hydroacoustic techniques to herring management (Fig. 2). Thus, while improvements are conceivable and may be dictated by the future development of the fisheries and increased understanding of optimal exploitation rates, the present procedures provide a sound interim approach with a timeliness which is rarely achieved in fisheries management.

HYDROACOUSTIC INDICES AS INPUT TO DYNAMIC MANAGEMENT SYSTEMS OF FISH STOCKS

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ABSTRACT

A case is made for introducing real-time management systems that set harvest limits while the season is in progress. Such a need results from our present inability to predict in advance run sizes with sufficient accuracy whereby harvest in relation to goals for escapement and spawn deposition can be maintained.

The migration of maturing fish populations into restricted spawning regions displays timing and behavioural characteristics controlled by specific genetic systems. Knowledge of these characteristics is used to calculate time-density probability functions, which provides an opportunity to predict the final run size on the basis of relative abundance indices aquired while harvest is in progress.

Traditionally abundance estimates have come from catch and test fishing data. It is argued that hydroacoustic methods of stock assessment are preferable because of accuracy and ability to rapidly cover large areas which is essential when monitoring fish runs.

RESUME

Une étude est en cours pour introduire des systèmes d'aménagement concrets qui limitent les prises pendant la saison de pêche. Ce besoin résulte de notre incapacité actuelle à prévoir par avance la densité des migrations avec suffisamment de précision; la relation entre la fuite et le frai peut donc être maintenue.

La migration de bancs de poissons adultes dans des zones de frai protégées démontre la synchronisation et les caractéristiques de comportement relatives aux mécanismes de contrôle génétique spécifiques. La connaissance de ces caractéristiques est utilisée pour calculer les fonctions de probabilité temps-densité qui permettent de prévoir le volume final des migrations sur la base d'indices d'abondance relative obtenus au cours de la prise.

Traditionnellement, les prévisions d'abondance émanent de renseignements sur les prises et tests spécifiques. Il est prouvé que les méthodes hydro-acoustiques d'évaluation sont préférables vu leur précision et leur facilité à couvrir rapidement de grandes surfaces, ce qui est essentiel dans le contrôle des migrations de poissons.

1. INTRODUCTION

Management of renewable aquatic resources is undergoing far-reaching changes at the present time, both in basic policies and methodology. The role of deterministic populations models with maximum sustainable yields is changing as the goals of contemporary management are shifting toward preserving spawning populations or spawning biomass rather than guaranteeing estimated yields and catch quotas.

These changes led to a need for real time fishery management. Data required for in season estimates of run size has been derived from a variety of sources, including visual counts, commercial catches and test fishing. Hydroacoustic methodology, using scientific grade equipment, has recently gained credibility as an integral part of the estimation process. Three cases employing hydroacoustics as a run size estimator are discussed below.

2. DYNAMIC MANAGEMENT SYSTEMS

Certain behavioural characteristics are common to many aquatic organisms which are commercially exploited. Salmon, as well as most fish species at higher latitudes with pronounced seasonal variations in climatic regime, temperature, light, and precipitation display migrations or accumulations synchronized to either feeding or spawning. Once a process has been initiated it proceeds in a regular, predictable manner. Any type of abundance indices taken at fixed intervals will, after normalization, depict a probability density function of the migratory or accumulating process. Mathematically it can be approximated and described by a normal probability curve (Mundy and Mathisen, 1981), or by a gamma function (Reilly, 1981), or by an empirically determined probability density function (Hornberger and Mathisen, 1982).

In the latter case the general approach is to calculate

$$P_k (X_i) = \frac{n_{ik}}{N_k} \tag{1}$$

where n_{ik} = observed abundance from input like catch, catch per unit effort, or acoustic indices in year k for time unit X_i

N_k = the seasonal sum of these indices

X_i = time units

Since $0 \leq p_k (X_i) \leq 1$ and they sum to one, these quantities form a probability distribution.

Next, an average probability is computed from

$$\overline{P(X_i)} = \frac{\sum_k^m P_k(X_i)}{m} \tag{2}$$

where m = the years for which data are available.

The distribution function is of the form

$$F(X_i) = \sum_{i=1}^{i} \overline{P(X_i)} \tag{3}$$

where i = the number of chosen time units (days, weeks, or any convenient unit).

The final step is to compute an in-season population estimate (Walters and Buckingham, 1975):

$$\hat{N}_{ik} = \frac{\sum_{i=1}^{i} n_{ik}}{F(X_i)} \tag{4}$$

Confidence limits can be placed on this estimate directly where a functional form is used for the migratory probability density function from the corresponding moment generating functions, or they can be approximated by the delta method (Seber, 1973) or simply calculated empirically from observational data.

2.1 Hydroacoustic Indices in Quinault Lake Management System

2.1.1 Geographic and faunistic features

The Quinault River watershed is a small drainage on the west coast of the State of Washington. Several species of salmon are found there, but the most prominent is the blueback or sockeye salmon (*Oncorhynchus nerka*, Walbaum). The fishery, a gillnet fishery, starts in the riverine estuary and continues upstream for several miles. Average annual catches have been less than 40,000 salmon in the past decade compared to 153,000 in the 1940's. Upon escaping the fishery, the salmon migrate about 64 km to Lake Quinault, a small (15.4 km^2) lake which serves as temporary residence for 4-5 months until sexual maturity is attained. This behaviourial trait is an atavistic character stemming from the genealogical relationship to other blueback stocks in the Colombia River from which they separated several thousand years ago. This testifies to the strong genetic basis underlying the migratory time density function used in this management system.

Due to the high summer surface temperatures in this lake (approaching 20°C), the population of adult blueback salmon resides at 20 m depth, an ideal depth for hydroacoustic assessment.

2.1.2 Hydroacoustic data acquisition system

The system consisted of a modified 105 kHz Ross 200A echosounder, an interface amplifier, and an analog A.M. tape recorder. The system has been described in detail in Nunallee (1974).

Each survey consisted of 10 parallel transects orthogonal to the long axis of the lake and space approximately 600 m apart (Fig. 1). Calibration and echo data were recorded in a systematic fashion with replication of each transect as the survey progressed.

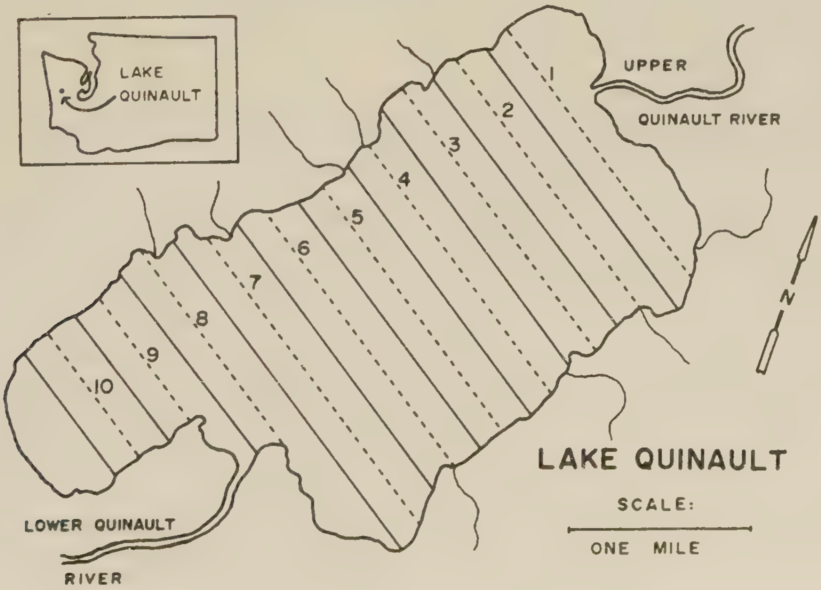

Fig. 1. Hydroacoustic transect lines established in Lake Quinault. Transects are indicated by dotted lines. Corresponding sampling areas are located between solid lines.

2.1.3 Analysis of the hydroacoustic data

Due to the relatively low densities of adult blueback, a procedure of visual (oscilloscope) echo counting was employed as described by Nunnallee (1974) and Lemberg (1975). Fish signals were easily recognized by their pulse length (0.6 ms) and the adults were segregated from other ichthyofauna by utilizing a -42 to -36 dB threshold. This effectively screened out all targets representing the smaller resident species. Species composition of the larger targets was determined from vertical gillnet sampling. Adult sockeye densities, by transect and depth were extrapolated over appropriate lake volumes to obtain population estimates.

Assuming that the adult population of maturing sockeye salmon in Lake Quniault has been assessed at regular intervals, these sequential population estimates reflect the distribution function of the escapement, which largely remains invariant under a constant exploitation rate scheme. However, this is not always the case, so a better approach is to take the increments in the acoustic lake estimates and lag them back to the time the fish passed through the fishery. In this particular system the average time lag is three days. Since the catches recorded by a conveniently chosen time scale, daily, twice weekly, or by weekly periods, are known, the entry pattern at time unit i is described by

$$N_i = C_i + E_{i-d}$$

where N_i = estimated abundance in time i

C_i = observed catches at time i

E_{i-d} = escapement lagged back by d time units

Because of the fixed timing of the migration and accumulation, the manager can each day assess whether the spawning stock is accumulating as expected for a given escapement goal. If not, the fishery is closed until the spawning stock has increased to the desired level before harvesting is resumed. Conversely, if the spawning stock accumulates faster than expected according to the historical data base, the fishery is kept open.

2.2 Salmon Escapements in Trunk Steams of Bristol Bay

2.2.1 Geographic setting

In Bristol Bay, Alaska, there are five major watersheds, each containing many lakes and spawning streams (Fig. 2). The maturing salmon approach the estuaries of these watersheds where the commercial harvest takes place.

Estimates of total population size can be derived from in-season estimates of daily abundance. These are calculated by combining catches and escapements, the latter ones estimated from the catches of a test fishery in the lower end of the trunk streams that fish move into after leaving the fishery and multiplied with a proper scaling factor.

Unfortunately, such daily estimates are recording events after harvest has taken place, and an excessive exploitation rate can only be remedied by lowering the exploitation rate in the future. If the time interval is minimized, a day in this case, miscalculations can quickly be compensated. For this reason, rapid assessment of the salmon leaving the fishery is essential. Factors contributing to the assessment problem include tidal fluctuations up to 7-8 m, peak time velocities approached 5 m/sec (10 knots), and glacial slit which limits light penetration to 15-20 cm.

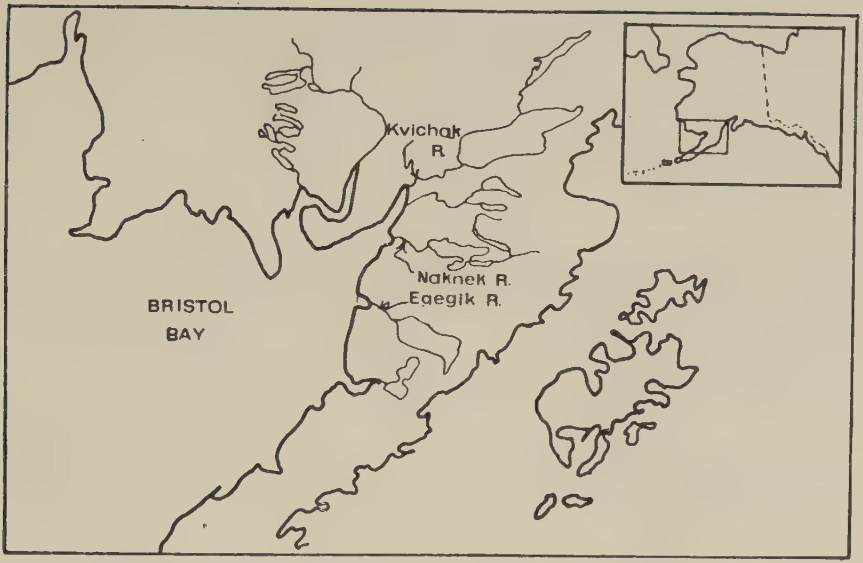

Fig. 2. Bristol Bay, Alaska, with the Egegik, Naknek, and Kvichak fishing districts.

2.2.2 Acoustic assessment system

Experiments have been in progress for several years to utilize acoustic assesment techniques. Initially, a standard data acquisition system, as described earlier, was used with a downward-looking transducer towed on the surface at high tide. But since most of the salmon are found in the upper 2 m of the water column, the sample volume, even with a 28-degree conical beam transducer, becomes miniscule. One redeeming feature of systematic observations with a high error component is the ongoing cancellation of errors in systems where the error is random and not inflicted with a consistent bias. Test fishing and acoustic indices are compared with each other in Fig. 3. Both methods yielded about the same results, but acoustic estimation is more time-consuming and required trained personnel.

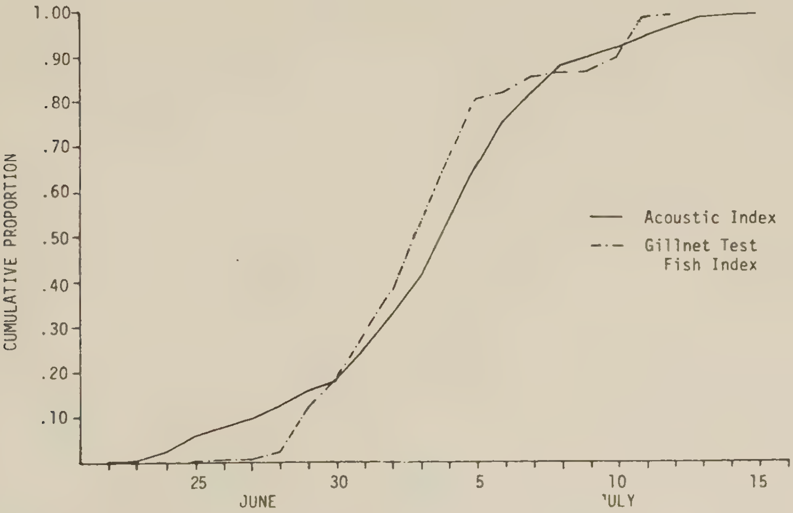

Fig. 3. Normalized cumulative indices for downward-looking acoustics, and gillnet test fish for the Kvichak River in 1977.

As an alternative, the transducers were placed on the bottom looking upward. By using a short pulse length, = 0.3 ms, the resolution near the water/air interface was maximized. In addition, the effective sample volume was variable and fluctuated with the tidal stage and water depth. Usually only one or two targets were insonified simultaneously.

2.2.3 Signal processing

To facilitate analysis in real time, a counter was developed (Whitt and Lahore, 1979; Whitt, Gaudet, and Johnson, 1980) which examined the envelope of the returned signal and differentiated among single, double, and multiple targets by comparison with expected pulse length. A printer recorded total target counts for each hour or any pre-set time unit. The sample volume was monitored continuously by sensing the difference to the surface which fluctuated with the tidal stage.

Although this system has performed well in large rivers like the Fraser River in British Columbia, Canada, mechanical problems are the main drawback to universal applications. The cost of placing the inverted transducer on the bottom of a stream and maintaining it in a swift river becomes prohibitive.

The basic question is if riverine sonars operating in the time domain represent the best solution. Recent interest has therefore focused on the use of the Doppler frequency shift brought about by ascending salmon or any moving object. The problem falls into tow parts depending on whether single or multiple targets are present. While the first case is much simpler and for which an operational model soon will be available, the multi-target situation must be approached in a manner similar to integration in the time domain, e.g., the total shift of energy spectrum must be summed (Dahl, 1982). Theoretically, there does not appear to be any obstacle to this approach, although the technical solution may offer some difficult problems.

3. REAL-TIME MANAGEMENT SYSTEMS

Because of the risk involved in harvest decisions, rapid and sequential updating of populations or biomass estimates is fast becoming not only highly desirable but mandatory in the management of renewable aquatic resources. Acoustic assessment methods are attractive because they provide speedy real-time data procurement and analyses in spite of the present cost and need of skilled operators. Two approaches include either conducting complete acoustic surveys during a sequential time frame or linking acoustic observations to fixed population characteristics (Fig. 4). By using the latter technique, estimated escapement is compared with the expected one for a given time period. The decision to harvest or not is determined by the difference between observed and expected estimates. Systems of this type with daily or frequent feedback loops achieve two principal objectives, namely, to preserve the necessary biomass and to prevent over-exploitation of any segment of the population, which enables the manager to make his daily harvest decisions on a rational basis.

3.1 Strait of Georgia Herring Fishery

Hydroacoustic assessment of marine species that exhibit known migratory or spawning aggregation behaviour can also be incorporated into the management system outlined in Fig. 4. The requirement is that a migratory probability density function can be constructed and the variance around the distribution function is small enough to provide early in-season usable estimates of the total population to be expected. The same is true when an accumulation takes place in a consistent manner with constant time spent in the aggregation. As an example, the herring fishery in the Strait of Georgia will be considered. This has been discussed earlier by Trumble *et al*. (1982).

In this fishery maturing herring (*Clupea harengus pallasi*) are intercepted before spawning, and the primary product is the egg skein or sac-roe. Catch is currently set at 20 per cent of the total estimated population biomass. The prespawners congregate during a three to four week period in a relatively restricted region adjacent to the spawning grounds and are harvested when they move onto the beaches (Fig. 5).

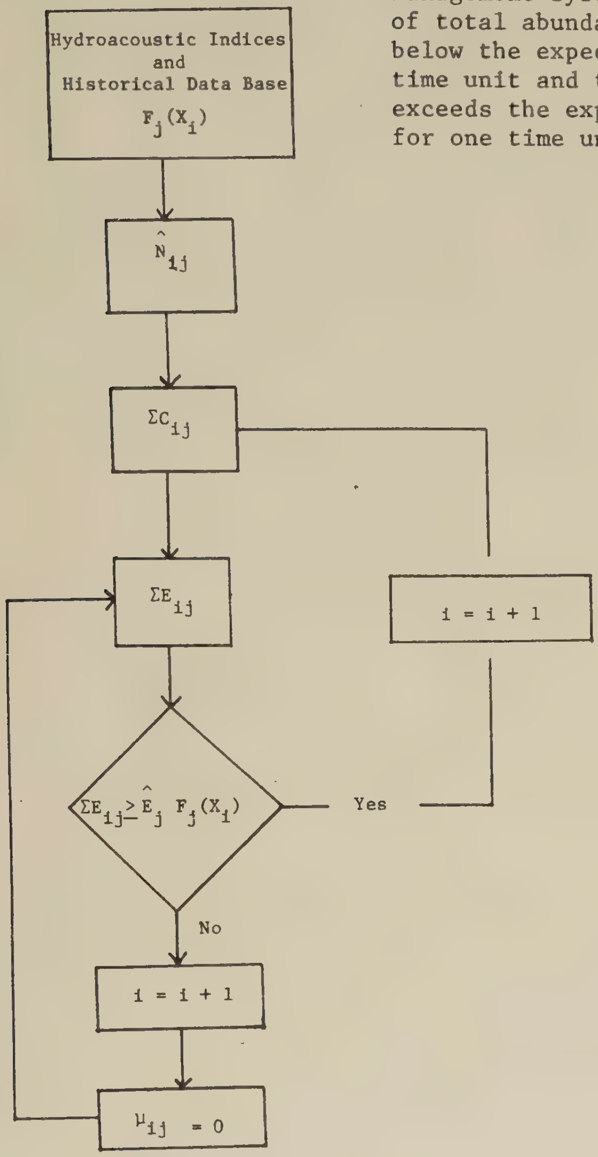

Fig. 4. Flow chart of decision process in a dynamic management system with regular monitoring and updating of total abundance. If the cumulative escapement falls below the expected value, the fishery is closed for one time unit and test performed again. First when $E_{i,i}$ exceeds the expected escapement is the fishery opened for one time unit.

i = time
j = location
X_i = relative abundance at time i
$F_j(X_i)$ = cumulative proportion of total abundance at time i at location j
$\hat{N}_{ij}$ = estimated, total abundance at location j at time i
$\hat{E}_j$ = desired escapement or spawning biomass at location j
C_{ij} = catch at time i at location j
μ_{ij} = exploitation rate at time i at location j
E_{ij} = escapement at time i at location j

Initially a modified Ross 200A was used and tape recorded data was processed on a land based PDP 11/45 integrator. Present onboard equipment includes a Biosonics model 101 echosounder, model 120 integrator, and a Kaypro II microcomputer to give real time data processing and analysis capability. Surveys are conducted by running a standard transect pattern twice weekly over the congregation area. All surveys are run at night, after the daytime aggregates found at 40 m disperse to form relatively uniform, widespread, single target layers between 10-30 m. Mid-water trawl sampling is carried out to identify species composition and herring maturity.

A hydroacoustic estimate of pre-spawning herring biomass has been obtained 6-10 times in each fishing season since 1976. If these estimates are normalized before plotting, the percentages observed at each time unit can be summed to produce an average cumulative probability density function. This could only be based on the two years 1976-1977, when sampling was complete enough to incorporate the entire accumulation period. Some irregularities of the average curve will disappear when additional years are incorporated. In subsequent years, reduced sampling truncated the cumulative distribution function on both sides. This was particularly true in 1980-1981, and an adjustment was made based on the average curve. The average cumulative distribution function and the variability around this for the years 1976-1978 are given in Fig. 6.

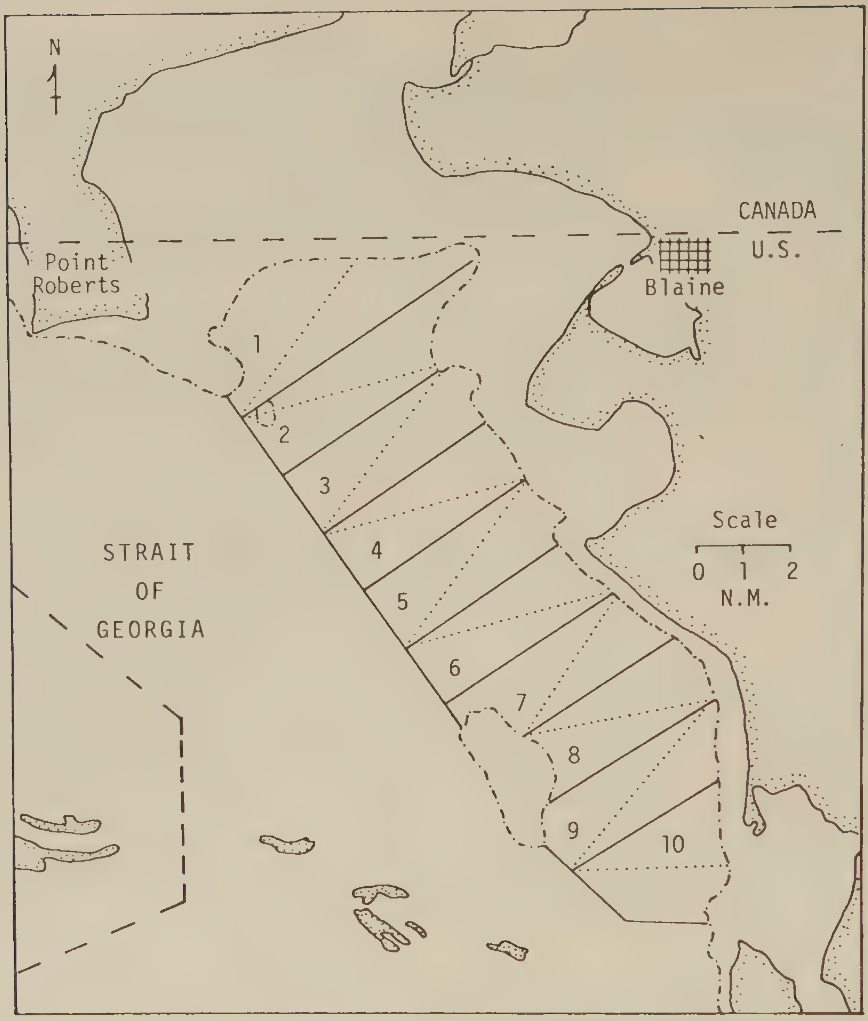

Fig. 5. Acoustic monitoring of accumulation of spawning biomass of herring (*Clupea harengus pallasi*) from 8-10 fms to 50-60 fms contour lines in the Strait of Georgia.

The variability implies that already after the initial acoustic survey, the total biomass of herring for that season can be estimated with an error acceptable for management purposes. This, then, provides a basis for estimating the total herring biomass to be expected according to equation (4). The data gathered in 1978 deviate more than the rest, which can be corrected by a translation along the time axis (Mundy and Mathisen, 1981) after a better average distribution function has been established.

4. DISCUSSION

Many large fish stocks all over the world are today in a depressed state as a result of excessive fishing pressure. Part of the problem stems from an inability to recognize the true abundance while fishing is in progress. An alternative is a real-time management system whereby harvest limits can be modified dependent on more accurate abundance estimates.

This has reached a highest degree of perfection in management of salmonid stocks, primarily because the escapement in many cases is visible and the escapement process lends itself to continuous monitoring. However, this alone is not very useful unless the migration follows a predictable path as expressed in the migratory probability density functions. These are now being investigated for various species and races of salmon; but they also seem to be valid for a variety of other marine species of fish and invertebrates. One potentially useful application is the assessment of arctic cod (*Gadus morhua*) which pass along the coast of northern Norway on spawning migration to areas further south.

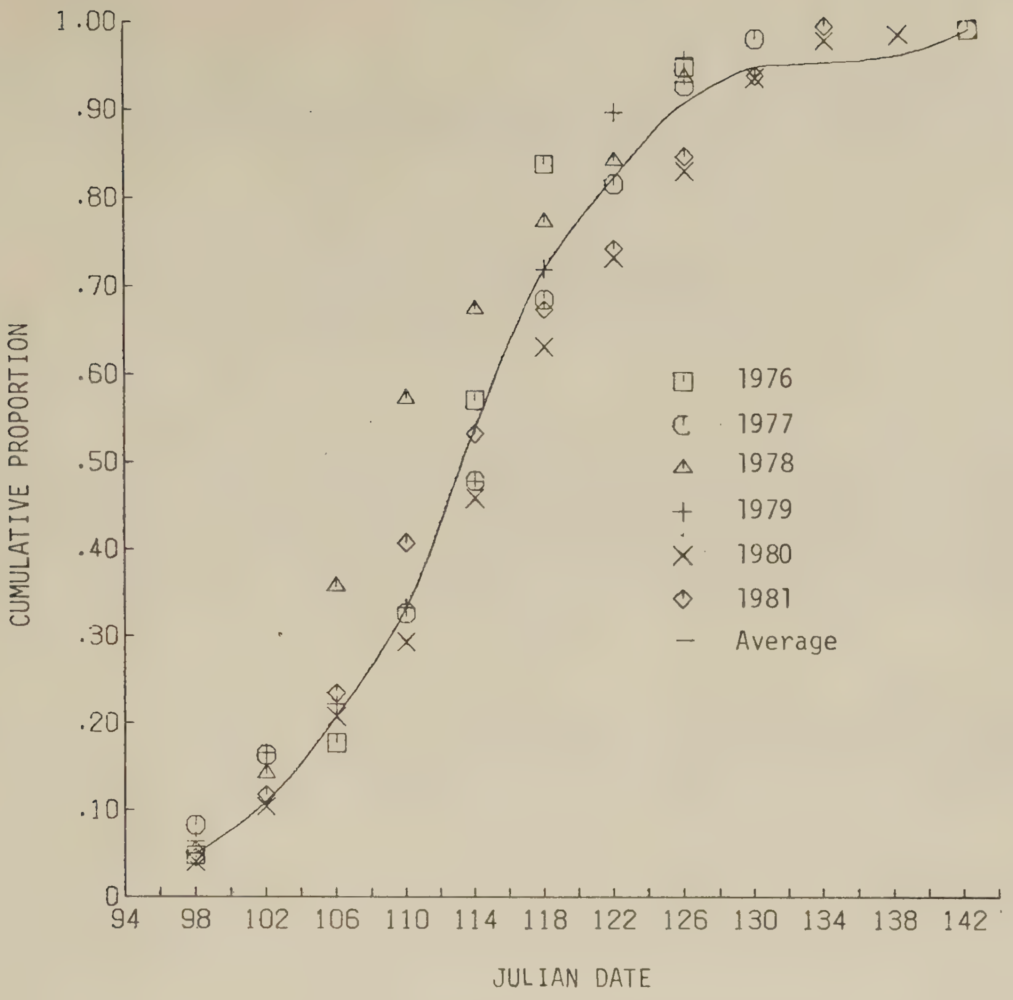

Fig. 6. Cumulative relative abundance of herring measured acoustically in the Strait of Georgia, 1976-1981, and the average distribution-function.

A next logical extension is to monitor accumulation of a spawning population, where arrival, build-up, and departure follow a pre-set series of events, controlled genetically although modified by the environment. The herring in the Strait of Georgia represent one case. The spawning concentration of mackerel (Scomber scombrus) in the southern part of the North Sea presents another potential application.

The utility of this approach is contingent upon two factors. First, precision is a function of the variability around the average migratory probability density function. However, if the genetic influence on migration or accumulation pattern becomes small relative to the effect of environmental factors like water temperatures, updating of total abundance estimates can only be given with very wide and therefore not useful confidence intervals. Next, if monitoring of relative abundance becomes too cumbersome and costly, the system becomes impractical. Acoustic monitoring of abundance, even without any attempt to scale the integrator values offer attractive future applications because of the speed of operation and real-time integration of received signals. Finally, no other technique for stock estimation is experiencing a greater growth potential today.

5. ACKNOWLEDGEMENT

The management system described here has been developing slowly during the last decade, especially in relation to salmon populations in Alaska with contribution from a number of biologists and graduate students. Part of this is recognized by citations in the text. A special thanks is expressed to Dr. G. Staufer for critically reviewing the manuscript and improving it through his comments.

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ABUNDANCE ESTIMATION OF DEMERSAL FISH IN THE BARENTS SEA BY AN EXTENDED ACOUSTIC METHOD

by

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ABSTRACT

A brief introduction into the fundamentals of the extended acoustic method is given . Special attention is paid to how we establish the integrator conversion factor of the actual species, and what to be aware of when observing near bottom fish. We discuss the survey design, the scrutinizing and preprocessing of data, and present results from the period 1976-1981 to illustrate the quality of the method. Since 1981 these results are directly used in stock management of the species concerned.

RESUME

Ce rapport décrit la méthode acoustique qui est pratiquée pour évaluer les stocks de morue et d'aiglefin de la mer de Barents. On s'est surtout attaché à expliquer deux points: comment on convertit la valeur d'écho-intégration en nombre de poissons, et les problèmes causés par des poissons qui se trouvent tout au fond de la mer.

Dans ce rapport nous avons discuté le projet de campagne, le dépouillement et le traitement des données. On discute également les résultats de la période 1976-1981. Depuis 1981 ces résultats sont utilisés dans la régulation des réserves de morue.

1. INTRODUCTION

In order to estimate abundances of fish stocks, considerable effort has been put into establishing efficient methods based on acoustics where echo integration has shown up to be the most applicable technique. Informations about observed fish abundances applied in stock management are reported by Buzeta and Nakken (1975), Nakken and Dommasnes (1975 and 1977) and Dalen and Smedstad (1979). Several other researchers report on more discrete investigations on fish abundance, for example Cushing (1968), Johanneson and Losse (1977), Peterson, Clay and Brandt (1976), Thorne (1973 and 1977) and Traynor and Ehrenberg (1979).

2. METHODS

2.1 Fundamentals of the method

When introducing the expression "extended acoustic method" we are incorporating other kinds of information than just the acoustical one from echo sounder and echo integrator. The extended acoustic method includes the following processes:

observing and recording integrated echo intensities by means of calibrated echo sounders and echo integrators,

identifying and distributing the recordings on species by means of biological samples, the echograms and the integrator readings,

determining the size and age distribution of recorded fish by means of biological samples,

applying mathematical models to estimate fish density, amounts of fish and distributions of length, weight and age.

The quality of each of these equally important processes and their interactive effects on the estimates will be considered based on own investigations and others (Bodholt, 1977; Ehrenberg, 1980; Ehrenberg, and Lytle, 1977; Foote, 1979; Shotton and Dowd, 1975 and Doubleday 1976). The schematics of the sampling and processing of data are shown by a block diagram in Fig. 1.

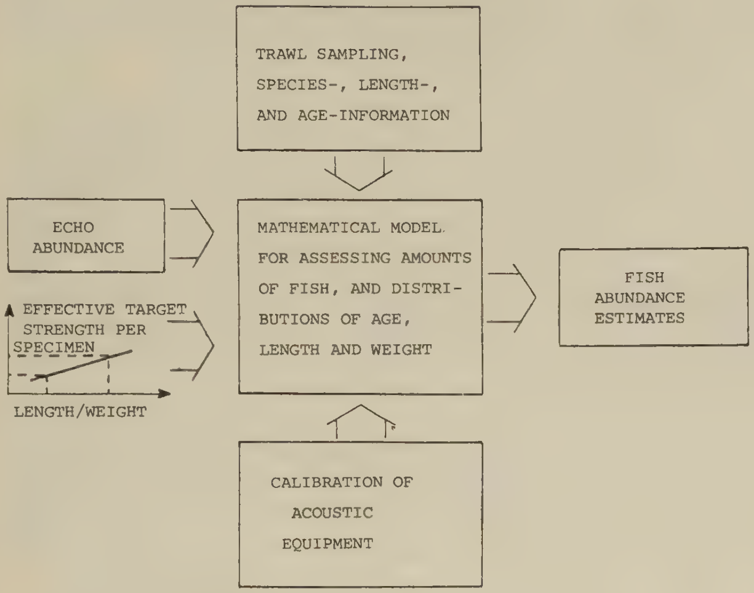
TRAWL SAMPLING, SPECIES-, LENGTH-, AND AGE-INFORMATION
ECHO ABUNDANCE
EFFECTIVE TARGET STRENGTH PER SPECIMEN
LENGTH/WEIGHT
MATHEMATICAL MODEL FOR ASSESSING AMOUNTS OF FISH, AND DISTRIBUTIONS OF AGE, LENGTH AND WEIGHT
FISH ABUNDANCE ESTIMATES
CALIBRATION OF ACOUSTIC EQUIPMENT

Fig. 1. The processes of the extended acoustic method for fish abundance estimation.

2.2 Echo integration

The backscattered echo energy is generally a function of the total abundance of the fishes being insonified, and the distribution of species and sizes. These distribution we may break down into what we define as a fish category which consists of a certain length group from a certain species.

The fish density and the integrated echo intensity bear a linear relation for each category "i". In matrix form this yields:

$$\underline{\rho_a} = \underline{C} \cdot \underline{M} - \underline{\rho_o} \qquad (1)$$

where

$\underline{\rho_a} = (\rho_{a1}, \rho_{a2}, \text{---}\ \rho_{aj}\ \text{---}\ \rho_{an})^T$, the area fish density vector with dimension 1 x n,

$\underline{C}$ = the integrator conversion factor matrix, a diagonal n x n matrix with typical elements C_j along the diagonal, other elements equal to zero,

$\underline{M} = (M_1, M_2, M_3\ \text{---}\ M_j\ \text{---}\ M_n)^T$, the echo abundance vector with dimension 1 x n, and

$\underline{\rho_o} = (\rho_{o1}, \rho_{o2}, \text{---}\ \rho_{oj}\ \text{---}\ \rho_{on})^T$, the threshold vector with dimension 1 x n.

The integrator conversion factor, $\underline{C}$, is besides being a function of the instrument characteristics such as source level, receiving sensitivity, system gain, and effective pulse length, a function of the average solid angle in which the particular fishes are observed and the effective backscattering cross section of fish under observation. This latter parameter is a multivariable function which takes care of species, length or weight dependences, modes of behaviour, spatial distribution of the fish, and the beam pattern function of the transducer.

The estimation of the effective backscattering cross section, $\langle\sigma\rangle$, or the effective target strength, <TS>, is a non-trivial problem. Two significant methods for making in situ measurements of <TS> were proposed by Craig and Forbes (1969) and Ehrenberg (1972). The methods, however, show to suffer from assignable statistical errors. Later Dunn (1977), Ehrenberg (1974 and 1978), and Robinson (1978) proposed different improved methods for directly measuring the target strength.

Analytical treatment of the problem based on target strength data observed under controlled conditions was demonstrated by Nakken and Olsen (1977), Love (1977) and Foote (1979). Comparing the conclusions of the two last-mentioned researchers to those from previous work (Ehrenberg and Lytle, 1977; Lozow and Suomala, 1972; Moose and Ehrenberg, 1971; Yudanov, 1977), their results seem to be more applicable due to more complete mathematical models, and more detailed information about the scattering properties of the fish.

Two direct ways to determine the integrator conversion factor should be mentioned (Johannesson and Losse, 1977; Midttun and Nakken, 1971 and 1977). One is "the cage method" while the other is "the counting of single fish method". The possibilities to carry out direct estimations of $\underline{C}$ is rather limited because of rather strong requirements to the composition and behaviour of the fish under observation, distinct knowledge of the insonified volume, and an accurate time varied gain generation within the the echo sounder. "The counting method" can, however, be applied with success in rather noncomplex biological systems. This has been done for spawning cod (Blindheim and Nakken, 1971), spawning blue whiting (Buzeta and Nakken, 1975), capelin (Nakken and Dommasnes, 1975), and juvenile cod and haddock (Dalen and Smedstad, 1979).

The established conversion factors we use for abundance estimation of cod and haddock are based on a combination of the results from two particular investigations applying the counting method (Anon, 1976; Dalen, Hylen and Smedstad, 1977a) together with an analytical one as described by Foote (1979).

The echo abundance, $\underline{M}$, might be expressed in absolute terms as for instance a certain recorder reading related to a specific reference input. It can also be expressed in logaritmic terms (decibels) which is equivalent to the volume backscattering strength.

$\underline{\rho_o}$ might be regarded as a threshold density. It determines mathematically the lower limit of the echo abundance for which equation (1) can be applied. On the other hand the magnitude and hence the effect of $\underline{\rho_o}$ can be controlled bythe threshold setting. Manipulation of this threshold with a watchful eye is very useful in supressing noise signals and signals from weak concentrations of smaller organisms. It should be stressed that as a particular effect of this threshold the integrator system generally discriminates against small targets as discussed by Ehrenberg and Weimer (1974) and Weimer and Ehrenberg (1975). This might bias the abundance estimates when the surveyed fish stock has a wide size composition.

2.3 Observing near bottom fish

When observing demersal species special attention has to be paid to the depth column close to the bottom. The parameters determining the detection of near bottom standing fish are as follows:

the beam angle of the transducer,
the effective pulse length,
the size of the fish targets,
the roughness of the bottom, and
the slope of the bottom.

The area over which the closest detection can be made depends on the beam angle, while the effective pulse length determines the closest point to the seabed at which detection is possible. Having a rough and uneven bottom the height of the largest rock or cliff will act as the effective bottom reference for each transmission. For a sloping ground the volume within which detection of fish can be made, decreases (Mitson, 1976).

We require that the echo sounder should have a narrow beam transducer and work with a short pulse length when observing near bottom fish populations. The resolution distance, d_r, which is the minimum distance from the bottom that fish can be detected as visible targets is for our equipment 0.7 m at 100 m depth to 1.2 m at 500 m depth. This is calculated from the following equation

$$d_r = d\,(1 - \cos \theta/2) + c\tau_e/2 \qquad (2)$$

where

d - depth of water
θ - full beam angle to half power level, for our system equal to 5.5°,
c - speed of sound, and
τ_e - effective pulse length approximately equal to $4\,\tau_{nom}/3$ (Mitson 1976)

It is necessary to have an integrator with a proper bottom stop function and also a bottom lock function.

2.4 Survey design

An over all objective is to try to minimize the effect of the known sources of error in the assessment methods and to optimize the estimation process with respect to all important parameters which influence the accuracy of the abundance estimate.

2.4.1 Biological basis

While developing the survey design we have been looking for favourable biological situations from the acoustic point of view for estimating young cod and haddock. Here we have considered differences in large-scale behaviour of the different age groups of the fish over the year cycle. In this context we have required:

surveying the species when it has the most advantageous spatial location or spread within its area of residence,
that the greater number of the fish have to stay off the bottom to be observed acoustically,
a minimum of movements of the fish within the surveyed area to minimize certain biases in the estimates, and,
not too strong mixing with other species.

For young cod and haddock in the Barents Sea we have found that the period January to the middle of March is favourable for applying acoustic methods. The juveniles and the young ones of the stocks, i.e. one to five-six years old fish, are then located in a rather well-defined area. They are slowly following the spawning migration of capelin in rather dispersed concentrations. They are mainly feeding on pelagic organisms as capelin, juvenile redfish, krill and shrimp which keep them to a greater extent off the bottom.

2.4.2 Survey grid and distribution of trawl stations

We are designing the survey pattern and distributing the trawl sampling to obtain the most precise abundance estimate for a given survey period. This is on the basis of:

the expected extension area of young cod and haddock,
the probable distribution of the species in the area,
the probable size distribution of the species, and
the large-scale behaviour patterns of the species.

Considering the large-scale biological sampling, this always takes place whenever the patterns of the echo recordings of demersal species change or when biological data is needed in response to distribution and coverage. Standard towing distance is three nautical miles to give an approximately equally swept volume both for demersal and pelagic trawl stations.

The survey pattern may generally be described as a zigzag path, crossing zigzag paths, parallel lines, or unsystematic lines to reach points selected at random. The variance of an abundance estimate will generally vary when choosing different survey patterns (Nicherson and Dowd, 1975; Shotton and Dowd, 1975 and Yates, 1965). On the basis of a survey period of five-six weeks and in order to cover the actual extension area of the species we have developed a parallel line pattern together with zigzag paths (Fig. 2). At an average the cource lines are equidistant, but slightly denser in areas with higher fish concentrations.

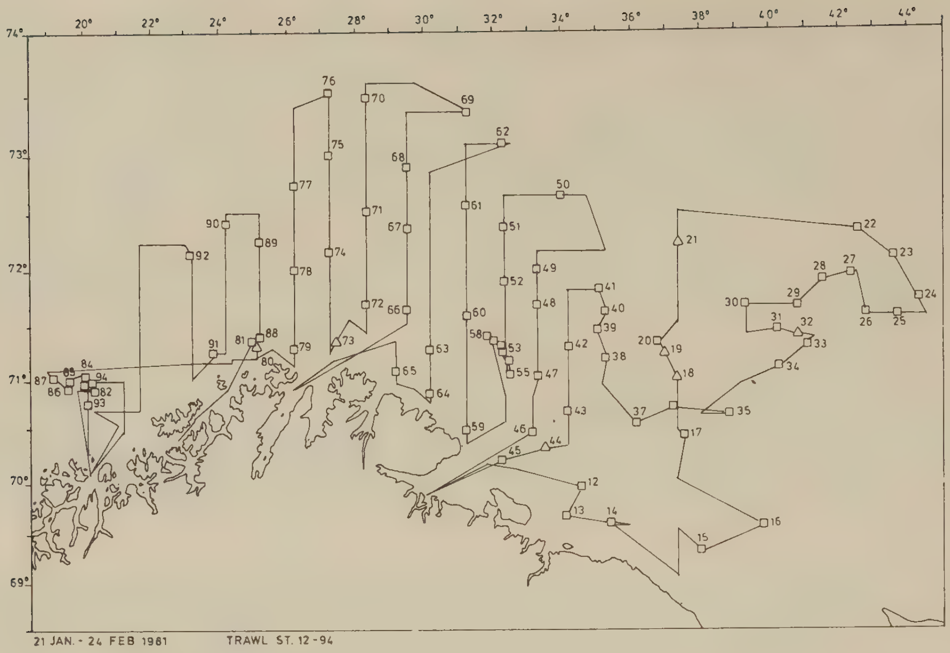

Fig. 2. Survey routes and trawl stations in January-February 1981. □ -bottom trawl, Δ-pelagic trawl.

The degree of coverage is ranging from 10 to 15 as defined by.

$$DC = L/\sqrt{A} \qquad (3)$$

where L is the total surveyed distance within the extension area A. This well defined survey pattern we conclude gives clearly comparable information about yearly changes of fish density, distribution, and size composition.

2.5 Instruments and sampling equipment

The vessel we have used, R.V. "G.O. Sars" is equipped with SIMRAD scientific echo sounders, both with hullmounted transducers and with towed ones. The particular sounders, EK 38 and EK 400, are working at 38 kHz, and are used with a nominal pulse length of 0.6 and 1.0 ms respectively, a band width of 3 kHz, and the beam width at half power level of the transducer is 5.5°, approximately circular.

The sounder is connected to a digital echo integrator system having eight depth channels. Up till 1980 we used an analogue system (SIMRAD QM MK II) having six depth channels.

As important as acoustical data are the biological ones when assessing absolute abundance of the actual species. Requisite biological data from ground fish we collect both with bottom trawls (Campelen shrimp trawl) and pelagic trawls (Mong Bas-trawl) with fine-meshed net in the cod end.

2.6 Scrutinizing and preprocessing of data

The main purpose of these activities is to attach the right echo abundance to all observed species or groups of species and to remove unwanted influences on the echo abundance from non- biological sources.

One or two daily scientific staff meetings are held to scrutinize the running information from:

the echo abundance observations - by echo sounder and integrator,
the biological sampling - by trawls,

the oceanographic sampling - by CTD-sonde, and
the wind and wave observations - to monitor any influence from wind- and wave-induced air bubbles on the acoustic data acquisition (Dalen and Løvik 1981).

The acoustic data are scrutinized and preprocessed both for mapping purposes and for the computer aided estimation of all relevant biological quantities.

3. SOME RESULTS FROM THE PERIOD 1976-1981

The winter time is usually very windy, and therefore varying amounts of the registrations are influenced by additional absorption of the tranceived echo energy (Dalen and Løvik, 1981). This effect has not been taken into account in a proper manner until 1981. It should also be noted that the results from the survey in 1980 is excluded from our analysis due to non-detected malfunctioning of our acoustic system.

The geographical distribution of cod have changed considerably during the years of investigation (Fig. 3). In the period 1976 to 1978 the distribution was easterly while from 1979 on we found a westerly distribution. This westerly change is caused by several factors. First there was an extreme cooling of the water in the eastern part of the Barents Sea in winter 1978-1979. This cooling forced the fish to migrate westwards. Second there is a general trend of the fish to move westwards with increasing age (Dalen *et al.*,1977a and b; Midttun, Nakken and Raknes, 1981).

Table 1 shows that one year old cod always are greatly underestimated and to some extent also those who are two years old. Fish older than 6 years are also underestimated because they are mostly distributed west and south of the investigated area. It is thus the age groups 3-6 that have been best estimated by this method in the Barents Sea. However, in the last years the investigated area has been extended westwards which give an improved estimate of 6 and 7 years old fish.

Table 1. Estimates on year-class abundances of cod (in millions), and the relative abundances compared with the VPA (ICES 1982).

	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	TOTAL 3-6 years
1976 AM						1002	58	309	212	83	110	714
% of VPA						81	14	49	45	35	36	44
1977 AM					45	882	104	315	139	52	47	610
% of VPA					8	87	30	72	49	119	33	51
1978 AM				28	235	797	153	172	25	14	17	1147
% of VPA				12	50	98	61	83	22	27	27	83
1979 AM			16	14	109	502	77	45	14	4		733
% of VPA			11	7	28	84	47	50	34	21		59
1981 AM	3	73	58	124	243	270	41	8	3	4		695
% of VPA		111	58	98	102	100	100	38	38	117		95

The abundances of the different year-classes found by the acoustic method are in good agreement with the 0-group indices (ICES, 1981). Both the 1973- and 1975 year-classes were found to be rich, but the 1973 year-class was much weaker than indicated by the 0-group index (Table 3). All year-classes after 1975 were poor at the age of 3 years. However, in 1981 the estimated number of the 1976 year-class had increased from 1979 to 1981. This increase may be due to misreading of the age of the 1975 year-class, but it is also possible that the increase was partly caused by the corrections of the integrator values for bad weather which were introduced in 1981.

Comparing the estimates from the acoustic method (AM) with the estimates from the Virtual population analysis (VPA) made by the Arctic Fisheries Working Group (ICES 1982), we find that the AM estimates of 3 to 6 years old fish increased from 44% of the VPA estimates for 1976 to 95% of the VPA estimates for 1981 (Table 3). However, in 1981

Table 2. Estimates on year-class abundances of haddock (in millions), and the relative abundances compared with the VPA (ICES 1982).

	1980	1979	1978	1977	1976	1975	1974	1973	1972	1971	1970	TOTAL 3-6 years
1976 AM						3165	69	54	30	12	5	101
% of VPA						909	46	93	91	71	10	64
1977 AM					267	755	198	60	10	9	12	277
% of VPA					107	268	171	171	67	112	52	159
1978 AM				111	149	737	55	1				793
% of VPA				148	73	346	122	11				297
1979 AM			17	11	181	251	13	+	2			445
% of VPA			23	18	110	189	65		67			139
1981 AM	2	25	14	66	160	50	43	1				290
% of VPA		25	28	161	205	116	67	100				137

Table 3. Year-class strength of cod and haddock from the 0-group survey, the acoustic method (AM) and the VPA made in 1981.

	COD			HADDOCK		
Year class	0-group index	N (age=3) AM	N (age=3) VPA	0-group index	N (age=3) AM	N (age=3) VPA
1973	684	309	627	54	54	58
1974	51	104	348	147	198	116
1975	343	797	816	170	737	214
1976	43	109	388	112	181	164
1977	173	124*	158*	116	66*	41*
1978	106	58	100	61	14	50

* age = 4.

the terminal fishing mortalities in the VPA were adjusted to fit the AM estimates for 4 to 7 years old fish. On the other hand from 1976 to 1981 there has been both an extension of the surveyed area and improvements of the method.

In 1978 we had extremely good weather, and the 1975 year-class which made up almost 70% of the 3 to 6 year old fish had an easterly distribution. The area investigated was from North Cape and eastwards, but still we got 83% of the VPA estimates. In 1979, however, the weather was windy, and even if the surveyed area was extended westwards, we got only 59% of the VPA estimates. As already mentioned the results from 1981 were directly used by the Working Group. We must, however, bear in mind that the Spitsbergen area, which also is a nursery area, has not been covered by these investigations. However, young cod have been found in very small numbers, off Spitsbergen in recent years.

The year-class strength of haddock estimated by the acoustic method are in good agreement with the 0-group indices (Table 3). There is, however, a great difference between the estimates of the 1975 year-class found by the acoustic method and the VPA. In the VPA the 1975 year-class comes out as an average year-class. It is only 21% of the 1969 year-class which was very rich. But both the 0-group survey and the USSR Young Fish Survey found indices for the 1975 year-class which were the highest on record (ICES,1982). This indicates that the VPA have underestimated this year-class seriously.

Table 2 gives the estimated abundances of the year-classes of haddock in the different years. Comparing these estimates with the VPA estimates we find that the acoustic method seems to overestimate the abundance of haddock. If we take into account

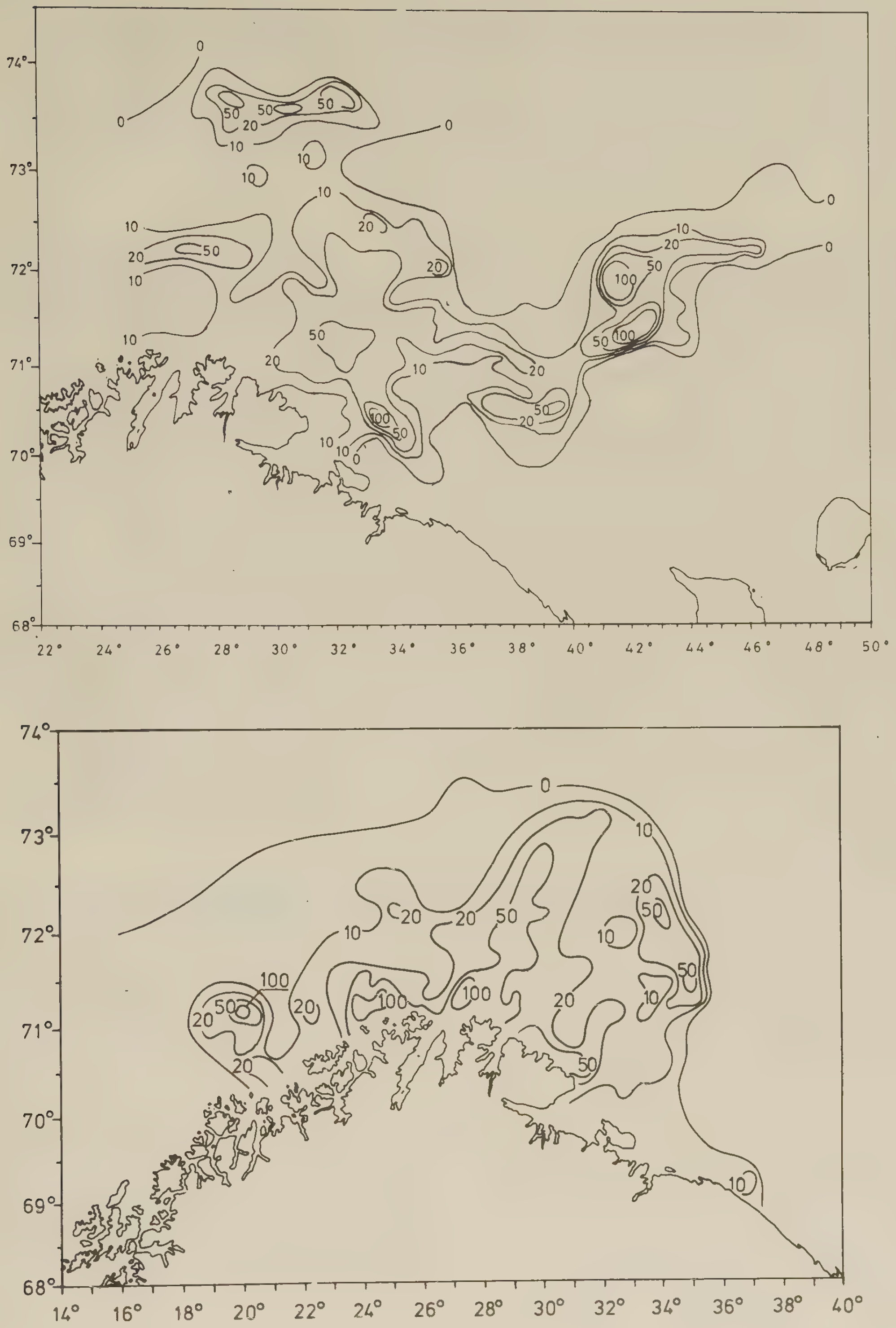

Fig. 3. The distribution of echo abundance of cod and haddock in the Barents Sea in winters 1978 and 1981.

that the VPA probably has underestimated the 1975 year-class seriously, the differences between VPA and AM estimates will diminish, but still there seems to be an overestimation of the haddock stock by the acoustic method. This overestimation can be explained if the catchability of haddock is greater than that of cod, because the splitting of integrator values for cod and haddock is dependent on the relative abundance of cod and haddock in the trawl catches. An overestimation of haddock will, result in an underestimation of cod.

ECHO SURVEYING OF THE ICELANDIC SUMMER SPAWNING HERRING 1973-1982

by

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ABSTRACT

During the period 1973-1979 the recovery of the Icelandic summer spawning herring has been monitored by hydro-acoustic abundance surveys using the Simrad echo integrator system. The surveys have generally been carried out in late November or early December when the herring have assembled in an overwintering area at South or East Iceland. The survey design and tactics are discussed and the results of the surveys are compared with fisheries data and the results of VPA. The two sets of estimates were found to be closely correlated.

RESUME

La reconstitution des bancs de harengs d'été et du frai, durant la période 1973-1979, a été enregistrée lors de campagnes d'évaluation hydroacoustique de la densité des bancs, réalisées grâce au système Simrad d'intégration des réponses sonores. Ces évaluations ont été généralement exécutées fin novembre ou début décembre, lorsque les harengs se sont regroupés dans une zone d'hivernage, au sud ou à l'est de l'Islande.

La conception et les motivations de ces contrôles sont discutées ici, et leurs résultats comparés à ceux des données des pêcheries et aux résultats VPA. Les deux ensembles de données se sont d'ailleurs révélés correspondre étroitement.

1. INTRODUCTION

Echo surveying of herring at Iceland has been conducted during more than 3 decades. The main purpose of these surveys used to be to chart the distribution and the movements of the herring and on that basis help the fishing fleet in catching herring. After the collapse of the herring stocks and the introduction of the Simrad integrator system the nature of the echo surveys changed completely. No longer were the surveys designed to help fishermen fishing more herring but the main purpose was to estimate the abundance of the herring stock with the view to carry out a realistic assessment of the stock and on that assessment to be able to advice on TACs.

Fishery independent methods for fish stock assessment were the theme of the Pelagic Fish Committee of ICES in 1980. As a response to that theme the present author gave an account (Jakobsson, 1980a) of the acoustic abundance estimates which had at that time been obtained on the Icelandic summer spawning herring. The purpose of this paper is to update the results described in that account especially in the light of new TS-measurements that have been carried out on the Icelandic summer spawning herring (Halldórsson and Reynisson, 1982).

2. TIMING OF THE SURVEYS

The timing of an echo abundance survey is of course very critical. It was decided in 1972 to investigate the feasibility of carrying out such a survey on the wintering grounds in November-December. The choice of survey period was based on the results of extensive echo-surveys from earlier years. These had indicated that during November-December the stock assembled in a limited and well defined area where a detailed survey could be carried out with relatively small survey effort. In recent years the feasibility of carrying out an echo-abundanced survey has been studied at other times of the year, e.g. in October and January-February, without positive results. However, during the winter 1981/82 surveys in November-December did not yield positive results while conditions in January were excellent.

Despite the fact that the surveys have with one exception been carried out at the same time of the year it should be noted that the actual survey tactics had to be changed to some extent from year to year according to variations in the behaviour pattern of the herring on the wintering grounds as will be described in the following section. Typical day and night concentrations of wintering herring are shown in Fig. 1.

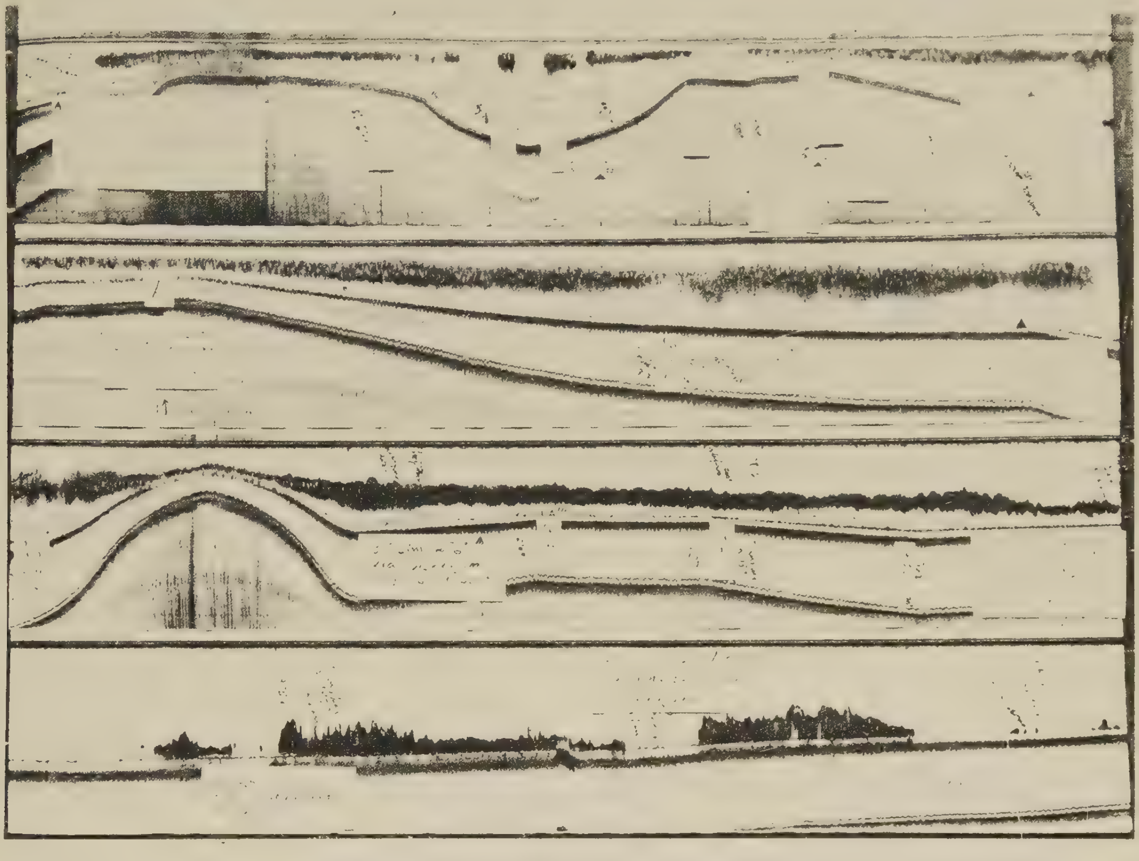

Fig. 1. Echograms showing the continuous layer of herring in midwater during the echo abundance survey 1974. The daytime concentrations on the bottom are also shown.

3. CONVERSION FROM ECHO ABUNDANCE TO FISH ABUNDANCE

In earlier papers (Jakobsson, 1978, 1980 and 1980a) the term echo abundance was used to describe the product of the area of the wintering schools (square nautical miles) and the mean echo intensity per sailed nautical mile measured as an elevation in mm on the Simrad echo integrator. When converting the echo abundance to fish abundance it was assumed that the integrated echo intensities were directly proportional to the weight of the fish. Using mean weight and age distributions on the wintering grounds the stock in number by age could then be calculated.

Norwegian scientists (e.g. Nakken and Olsen, 1977; Dalen et al., 1976) have obtained results which indicated that the echo intensities are related to the length of the fish rather than the weight. During the acoustic abundance surveys in 1980 and 1981 Haldórsson and Reynisson (1982) obtained a series of TS estimates for different size groups of herring. As shown by Halldórsson and Reynisson (1982):

$$\text{TS herring} = 21.7 \log l - 75.5 \text{ dB}$$

where l is the length of the fish.

Based on this TS equation and the instrument characteristics on board the R/V "Arni Fridriksson" the integrated echo intensity was converted to fish abundance using the equation

$$N = C \times M \times A$$

where N is the total fish abundance in numbers,

C is the number per unit area and is dependent on the length of the fish according to the equation:

$C = a \times 1^{-2.17} \times 10^6$ (number of fish/n.m.^{2}/mm elevation on the echo integrator, ref. 40 dB gain)

M is the weighted mean elevation in mm per sailed n.m. within the wintering herring school.

A is the area of the wintering school(s) in square nautical miles.

In 1980 this resulted in: $C = 17.2 \times 1^{-2.17} \times 10^6$ herring/n.m.^{2}/mm
and in January 1982: $C = 13.0 \times 1^{-2.17} \times 10^6$.

The difference is due to differences in instrument performance on board the ship. As described by Jakobsson (1980a) counting of single fish echoes in 1973 and using the method described by Midttun and Nakken (1971, 1972) gave 8000 herring/mm/n.m.^{2} (ref. 40 dB). These herring were all 1-ringers and their mean length was 21.6 cm with mean weight of 83 g. Therefore, this corresponds to 664 kg of herring/mm/n.m.^{2}. In earlier accounts (Jakobsson, 1980, 1980a) this relation has been used for conversion of echo abundance to fish abundance regardless of the size of the fish. In the light of the new length dependent TS equation one has for 1973:

$$8000 \text{ herring} = a \times 21.6^{-2.17} \times 10^6$$

and hence $C_{1973} = 6.29^{-2.17} \times 10^6/\text{mm/n.m.}^2$

Similarly the results for the period 1974-1979 were recalculated using the same length dependence as given in the TS equation above. The recalculated length dependent estimates are given in Table 2 using the mean weights and age distributions on the wintering grounds (Table 1) for calculating the number by age.

Table 1. Age distribution in echo abundance surveys 1973-1982.

Rings	1973	1974	1975	1976	1977	1978	1979	1980	Jan. 1982
	%	%	%	%	%	%	%	%	%
1	100	3	43	21	25	17	2	33	1
2		74	6	30	48	35	18	41	3
3		10	40	4	5	22	36	5	12
4		11	5	32	2	5	25	9	24
5		1	3	6	15	2	5	8	6
6		1	1	4	2	11	4	1	18
7			1	2	2	3	9	1	24
8+			1	1	1	3	1	2	3
9						2		1	1
10+									8

When using the age distribution in 1980 to split the stock estimate that year very high numbers (about 800 millions) were derived for 1- and 2-ringers. Thus these 2 year-classess would be much stronger than any other year-classes recruiting to the stock during the last 35 years. However, these year-classes have neither turned up in the fishery in 1981 nor have they been located in such very high abundance during the acoustic surveys in 1981-82. The acoustic estimate in 1980 has therefore been recalculated with the constraint that 1- and 2-ringers were 500 and 620 millions of herring respectively. In this recalculation the number of 2 ringed herring 1980 corresponds to the strongest year-class which has recruited to the stock since 1949 and the ratio between 1 and 2 ringed herring is kept the same as obtained in the samples in 1980. Thus a considerable proportion of the echo abundance which had been attributed to these two year-classes (ICES, 1981a) has now been redistributed onto the older herring. This is considered a more realistic approach than using the age distribution directly as obtained in the pelagic trawl samples.

4. THE JANUARY 1982 RESULTS AND THE INPUT F FOR THE VPA

An acoustic abundance survey was successfully carried out on the mature part of the stock in January 1982. The first estimate was obtained in the early hours of the morning of the 9th of January and another estimate during the following evening and the early hours of the following day. During the first night the herring were located in two schools, 4 and 7 n.m.^{2} (Fig. 2, upper). The following night the herring were located in 3 schools which were 5.0, 4.6 and 5.1 n.m.^{2} (Fig. 2, lower). The sum of products of the area and the average elevation in mm on the echo integrator per n.m. in each coverage is a direct comparison of the echo abundance recorded each night. This is shown in the text table below.

Echo abundance 9-10 January 1982

	Western school			Eastern school			
estimate 1.	A	M	AxM	A	M	AxM	Total AxM
9/1 1982	4.0 nm^2	1225	49000	7.0 nm^2	10090	70630	119630

	Western school			Central school			Eastern school			
estimate 2.	A	M	AxM	A	M	AxM	A	M	AxM	Tot. AxM
9-10/1 1982	5.0	13458	67952	4.3	6311	27134	5.1	6540	33354	128440

where A is the area in square nautical miles and M is average elevation in mm on the integrator (ref. 40 dB) per sailed n.m. within the school of herring.

Although there is a considerable variation in echo abundance between the schools of herring from one night to the other the difference between the total echo abundance is very small or only 7%. It is of course debatable whether to use one or the other of the estimates or the average of the two. In this case the first and lower estimate was chosen as the best one mainly on the grounds that the coverage of the schools was better during the first night than during the second one. This echo abundance was converted to fish abundance using the TS equation given in section 3 and the results are shown in Table 2. The ratio between stock in number and catch in number of 4 years old herring and older was used to calculate the input F for 1981 and these Fs were used to initiate the VPA given in Table 2.

5. COMPARISON OF THE VPA AND THE ACOUSTIC ESTIMATES

The stock estimates obtained by VPA for the last few years are still dependent on the input Fs which were derived from the results of the last acoustic estimate (Jan. 1982). When comparing the two sets of estimates, i.e. the VPA and the acoustic abundance estimates, it is also important to note that the results of e.g. the 1974 acoustic survey correspond to the 1975 VPA adding a year to the age of the fish. The reason for this is that the echo abundance surveys were carried out at the very end of the year (except in 1981/82) while the VPA estimates refer as usual to the 1st of

Table 2. Comparison of acoustic estimates (Ac) of the Icelandic summer spawning herring (in millions of fish) 1973-1980 and corresponding estimates from VPA.

	Rings	1973 1974	1974 1975	1975 1976	1976 1977	1977 1978	1978 1979	1979 1980	1980 1981	1982
Ac	1	211	7	184	60	293	216	26 1)	500 1)	23
VPA	2	448	112	167	623	446	126	372 1)	349 1)	
Ac	2		179	26	86	563	444	234	620 1)	99
VPA	3		402	99	141	546	382	100	323 1)	
Ac	3		24	171	12	59	279	468	110	206
VPA	4		52	335	86	105	446	301	70	
Ac	4		27	21	92	24	63	325	218	54
VPA	5		45	41	269	68	82	338	213	
Ac	5		3	13	17	176	25	65	232	157
VPA	6		16	33	31	201	54	59	242	
Ac	6		2	4	12	23	140	52	41	205
VPA	7		5	14	25	21	145	41	42	
Ac	7			4	6	23	38	117	36	30
VPA	8		3	4	11	18	13	107	28	
Ac	8				3	12	38	13	72	10
VPA	9		1	2	3	9	10	9	78	
Ac	9						25		13	57
VPA	10			1	3	4	9	14	6	
Ac	10									12
VPA	11								10	
Ac 3+			56	213	142	317	608	1040	722	731
VPA4+			122	430	428	426	759	869	689	
Ac 4+			32	42	130	258	329	572	612	525
VPA5+			70	95	342	321	313	568	619	

1) Inefficient estimate

The last group is a plus group

January each year. In Table 2 the two sets of estimates have been arranged in this way for easy comparison.

It is clear from Table 2 that the acoustic estimates for the period 1973-1976 were far too low for all age-groups. There can be several reasons for this. The survey technique was still developing in those first years and similarly the physical calibration technique had not reached the same level of accuracy as to-day. The low estimate of the 1971 year-class in 1973 is almost certainly due to the fact that 1-ringers recruit only partially to the wintering grounds at S or SE Iceland. The very low estimate in 1976 was at the time attributed to reduced instrument performance and therefore an attempt was made to obtain another estimate in Jan. 1977. By that time the wintering school had dispersed and the attempt failed. In 1977 the difference between the acoustic and the VPA estimates is smaller than in former years. Thus the difference between 2-ringers and older in the two estimates is only 11%. For 3 year and older herring the difference is somewhat higher and for 4 years and older herring the difference is about 20%. The difference in 1978/1979 for 2 years old herring and older is only 8% between the two estimates. There is a somewhat higher difference between 3 year old and older (20%) but the two estimates for 4 year old fish and older are practically equal. In 1979 and 1980 there is a great variation between the two estimates for 1 to 3 ringers. It should also be kept in mind that the VPA estimates for the top right hand corner of the VPA table are of course very uncertain in the absence of fishery independent information on the recruiting year-classes. But as regards the estimates of 4 year old herring and older the two estimates in both years are almost identical.

As mentioned above the results of the echo abundance surveys have been used since 1977 to calculate the fishing mortality generated by the herring fishery in the season immediately preceding each survey. In 1977 and 1978 one expected that 3-ringed and older herring were fully recruited to the fishery. In the text table below estimates of fishing mortalities for the Icelandic summer spawners are given for these two years:

	1977 F_{3+}	1978 F_{3+}
Concurrent acoustic estimate	0.27	0.21
Revised estimate	0.25	0.18
VPA estimate	0.19	0.15

It should be noted that the only difference between the concurrent acoustic estimate and the revised estimate is that in the latter, an account has been taken of the length dependent TS values.

As from 1979 it was realized that the summer spawning herring was not fully recruited until they were 4-ringers and therefore the adult F was calculated from the acoustic estimate of 4-ringed fish and older (instead of 3-ringers) and the catches of the corresponding year-classes which were taken in the fishing season immediately preceding the acoustic estimates. In the text table below these F values are given for the period 1977-1980.

	1977 F_{4+}	1978 F_{4+}	1979 F_{4+}	1980 F_{4+}
Original acoustic estimate	0.25	0.24	0.23	0.33
Revised acoustic estimate	0.23	0.20	0.19	0.24
VPA estimate	0.19	0.22	0.19	0.24

It is noted that the difference in fishing mortality between the two sets of acoustic estimates in 1977 and 1978 has been reduced considerably. This is probably due to the fact that some of the 3-ringed herring had not recruited in those years and therefore it was unrealistic to use the same F for 3-ringers and older herring. During the period 1977-1980 the difference between the calculated fishing mortalities based on the revised acoustic estimates and the VPA are negligible in all years.

It is also noted that there is a great difference between the concurrent and the revised estimates of adult F in 1980. As mentioned earlier the main reason for this difference is that in 1980 the herring was in very narrow fjords. The densest concentrations were very close to the shores of the fjords and therefore the sampling with pelagic trawl was most difficult. The inefficient sampling of the herring concentrations in these small areas is considered to be the cause for the great over-estimation of 1- and 2-ringers and the corresponding under-estimation of older herring in 1980. In the revised calculation a constraint was put on the abundance of 1- and 2-ringers and the echo abundance was transferred to the adult herring.

In Fig. 3 the VPA stock estimates for adult herring are plotted against the hydroacoustic ones. The correlation is highly significant especially if the 1976 acoustic estimate is discarded for the reasons given above.

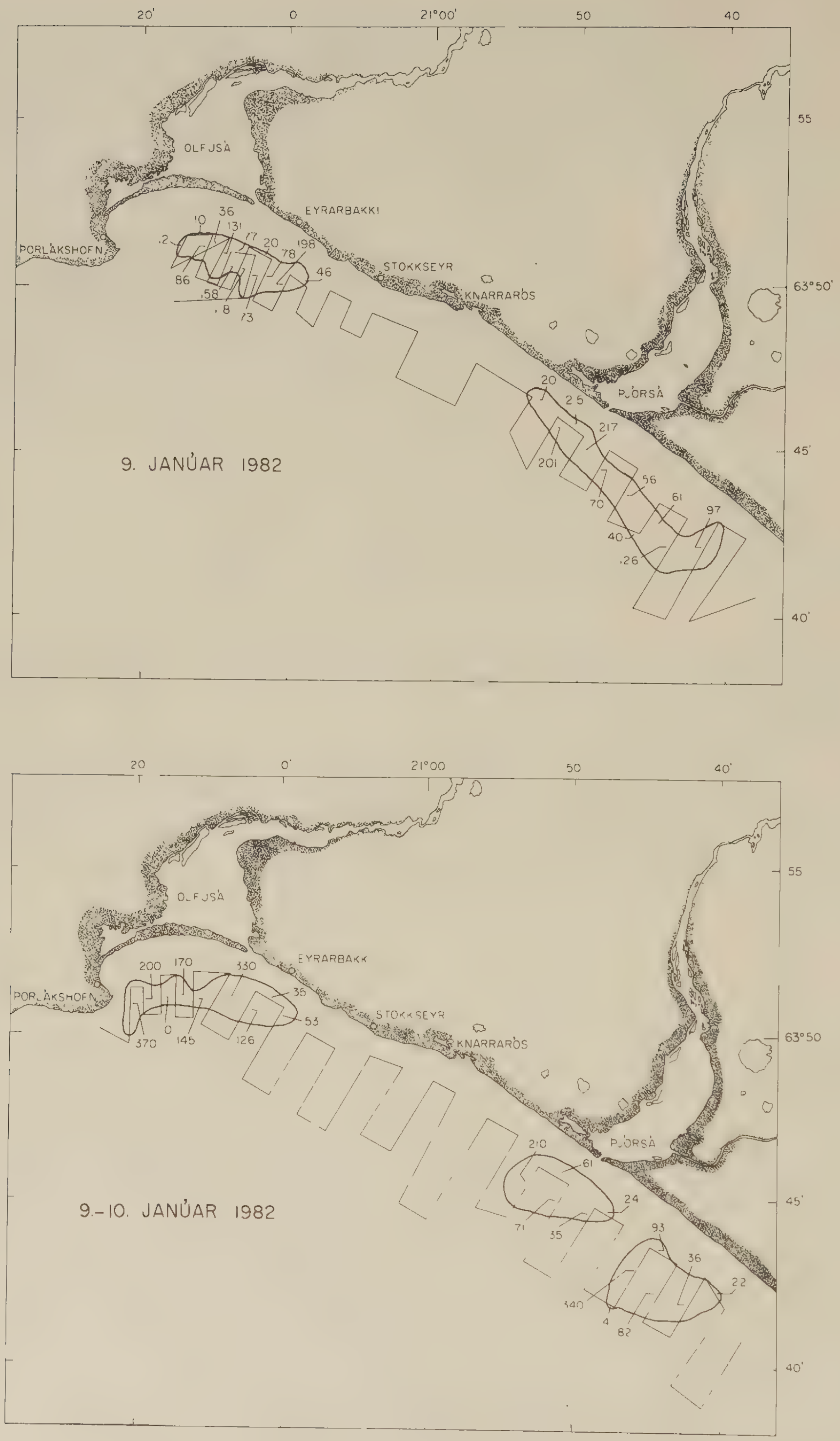

Fig. 2. The wintering concentrations in Jan. 1982. Echo intensities and distribution is shown on two successive nights.

6. DISCUSSION

Midttun and Nakken (1977) and Suomala and Yudanov (1980) have emphasized that the optimum conditions for gathering acoustic data are: calm wind and seas, a single species of fish of uniform size and stable behaviour, and distribution of the fish in a continuous layer of uniform density, away from the surface and the bottom. It is clear that the optimum conditions for an acoustic abundance survey include all of these plus perhaps the most important factor, i.e. a thorough understanding of the distribution, both in space and time, of the fish population concerned.

Although these optimal conditions cannot be met in all respects in the echo abundance surveys on the Icelandic summer spawning herring it is of interest to note that in many ways conditions are favourable. Although the Icelandic area is not known for calm wind and sea in mid winter practically all the abundance estimates have been obtained under these conditions. This is because these estimates can be obtained in a few hours after the necessary preparatory work has been done.

The waiting for the ideal weather conditions has on the other hand often been long, even more than a week. When the herring have assembled in the wintering area, mixing with other species has been negligible so for all practical purposes one can say that in this respect one has a single species of fish but with the exception of 1973 they have not been of uniform size.

The behaviour has not always been stable but by studying the changes that have taken place it has been possible to adjust the survey tactics to these changes. The herring have, for instance, sometimes been very close to the bottom during the day. Usually the density has then been very high and the bottom stop on the integrator could not be used due to the whiteline effect. At night on the other hand the herring have often been so close to the beach that there has been insufficient waterdepth for the vessel and in any case in such very shallow water the ship's disturbance of the herring will almost certainly be very pronounced. Therefore one could draw the conclusion that the echo integration was not possible because it could neither be carried out at night nor during the day. However, by selecting the time in the early hours of the morning when the herring is slowly migrating to deeper waters, but has not quite descended to the bottom, almost optimal conditions have been encountered for carrying out the echo abundance survey. Nothing of this kind could of cause be done without a thorough knowledge of the general distribution and migration pattern of the herring. If for instance the survey effort had been more or less random in Icelandic waters with the course lines, say 20-40 n.m. apart the wintering school might not have been detected at all or at most one section might have passed through it, probably at the wrong time of the day! But how does one know that there is perhaps not another concentration in quite another part of the sea at Iceland? During the last few years one has had the opportunity to carry out an echo abundance survey at the end of the 2-3 month fishing season. Since some 140 boats participate in the herring fishery it is possible to follow very closely the development of the fishing areas and study how these converge towards the overwintering area. In order to complete this picture a research vessel acoustic survey has been carried out each year 2-3 weeks prior to the echo abundance survey. During this preparatory survey, areas not kept under surveillance by the fishing fleet have been searched. The combined information from the research and the fishing vessels have, especially in the last few years, been so extensive that it is most unlikely that an important part of the stock could have escaped attention.

The experience from the winter 1981/1982 when the herring did not assemble in a wintering area until January instead of November - December makes it essential to have access to flexible research vessel time.

The most important test of the results of these echo abundance surveys is of course that they can be checked against fisheries data using the VPA. As yet, however, the two sets of results are still interdependent to some extent. Despite this interdependence of the two unlike methods it is quite clear that the estimates from 1973 to 1976 are under-estimates. During these years the main component of the stock consisted of one year-class. The underestimates in 1973 are probably due to the fact that this year-class had not recruited to the adult stock at the time. In 1976 the underestimate could also be due to decreasing performance of the hydro-acoustic equipment as discussed above. Another reason could be that the survey technique had not fully developed at the time. It is important to note that the present author was very much aware of these uncertainties and the difficulties in converting acoustic abundance to fish abundance. During the period 1973 to 1976 no attempt was therefore made to use the results of the acoustic surveys directly to calculate stock size and fishing

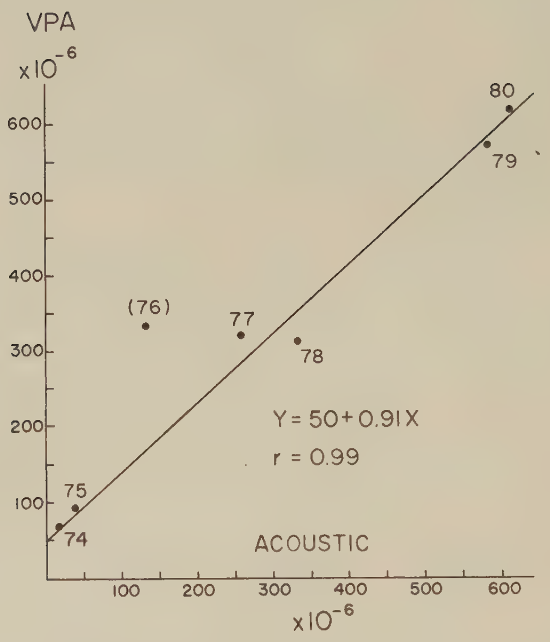

Fig. 3. Regression of hydroacoustic stock estimates (4 ringers and older) on VPA. The 1976 estimate is not included in the regression equation.

mortality. The results of the acoustic abundance surveys were only used as indications of how the stock was developing. It is only during the last 5 years or since 1977 that physical calibrations, conversion factors, improvements in survey techniques and such things have made one confident enough to use the results of the hydro-acoustic surveys directly for stock assessment and fisheries management.

It is quite clear (Fig. 3) that the hydro-acoustic surveys in 1977 to 1980 agree very well with stock assessment based on fisheries data. It is also of interest to note that according to the results in January 1982 the acoustic surveys do not only agree well with fisheries data but under good conditions the variation between two successive hydro-acoustic estimates is very small and would not make any difference to advise in fishery management. Therefore it is concluded that the hydro-acoustic surveys have become an excellent and efficient tool in monitoring the recovery of the Icelandic summer spawning herring and they give firm bases for advice on fisheries management. So far the hydro-acoustic surveys have mainly been concentrated on the wintering grounds. Since the young recruiting year-classes do not always mix with the adult component on the wintering grounds it is necessary, in order to be able to assess the young recruiting year-classes, to enlarge the survey effort so as to include the immature component of the stock.

ACKNOWLEDGEMENTS

I am much indebted to Olafur Halldórsson and Páll Reynisson. The results of their TS studies for herring in Icelandic waters have been invaluable in preparing this paper.

A COMPARISON OF THE RELIABILITY OF ACOUSTIC ESTIMATES OF FISH STOCK ABUNDANCES AND ESTIMATES OBTAINED BY OTHER ASSESSMENT METHODS IN THE NORTHEAST ATLANTIC

by

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ABSTRACT

The basic data for this analysis are fish stock abundance estimates presented in annual reports of ICES stock assessment Working Groups and other literature. These estimates are obtained by using various observation- and assessment methods; acoustic surveys, use of commercial catch and effort data, tagging experiments, egg and larvae surveys and fishing surveys. The values are analyzed with respect to the relative and absolute errors and the results for the different assessment methods are compared. It is shown that although one particular method might give fairly presice estimates of certain parts of a stock, in most cases a complete and reliable estimate of the total stock must be based on several methods. In particular, judging from the results achieved, acoustic surveys are potentially a key method for assessing stocks of small short- living pelagic fish and also for estimating young fish component of some demersal stocks.

RESUME

Les données fondamentales utilisées dans cette analyse sont les diverses estimations de l'abondance des stocks de poisson présentées dans les rapports annuels des groupes de travail du CIEM sur l'évaluation des stocks et autres documents. Ces estimations sont obtenues par différentes méthodes d'observation et d'évaluation: prospections acoustiques, utilisations de données commerciales sur la prise et l'effort, expériences de marquage, études sur les oeufs et larves, et pêches exploratoires. Les valeurs sont analysées du point de vue des erreurs relatives et absolues et les résultats des différentes méthodes d'évaluation sont comparés. Il est démontré que, bien qu'une méthode particulière puisse donner des estimations assez précises de certaines parties d'un stock, dans la plupart des cas, une estimation complète et sûre du stock total doit s'appuyer sur plusieurs méthodes. En particulier, si l'on en juge par les résultats obtenus, les études acoustiques constituent potentiellement une méthode clef pour l'évaluation des stocks de petits poissons pélagiques à courte espérance de vie, ainsi que pour l'estimation de la composante juvénile de certains stocks démersaux.

1. INTRODUCTION

Reliable acoustic estimates of stock sizes should be expected when the following requirements are met:

> Sufficient knowledge is available of the scattering properties of the species and size groups which are being recorded.
>
> Representative samples of the scatterers are being collected.
>
> The survey coverage is sufficient regarding the geographical distribution patterns of the fish.
>
> The survey is "synoptic", i.e. fish migrations within the survey area during the survey can be neglected.

In all practical survey work one will have to accept limitations regarding these points and errors will thus be introduced to the estimates. It is difficult to obtain quantitative information of the errors involved. The estimates originate from a variety of data and information - species and size compositions in trawl catches, empirical or in situ measurements of scattering cross sections, knowledge of fish migration and behaviour patterns in relation to survey grids - which all may introduce both biases and variances of often unknown magnitudes. Thus estimates of errors, or confidence limits to stock estimates, can seldomly be given for each particular survey. However, when different independent assessment methods are applied for the same stock, and/or when the stock is surveyed and assessed several times, for instance in subsequent years, likely sizes of errors or variances can be estimated.

In this paper stock sizes estimated during some previous years have been compared with estimates for the same years in the latest assessments available, the latter ones being taken as "true" stock sizes. The stocks and methods which have been considered are:

Stocks	Assessment methods
North-east arctic cod	Virtual population analysis (VPA) Acoustic surveys
North-east arctic haddock	Virtual population analysis Acoustic surveys
North-east arctic saithe	Virtual population analysis
North Sea cod	Virtual population analysis
Barents Sea capelin	Acoustic surveys
North Sea mackerel	Virtual population analysis
Western mackerel	Virtual population analysis

The procedure which has been applied utilizes the convergence nature of VPA estimates. Relative errors in estimated stock sizes from VPA decrease towards fairly small values as one calculate the strength of a year class backwards, the rate of convergence towards the true value being dependent on the level of fishing mortality (Pope, 1972). However, there are several factors which could disturb this convergence. Pope (1972) discussed the effect of sampling (random) errors in catch in number by age data which will cause a variance on estimated stock sizes. Ulltang (1977) discussed the effect of errors in the assumed value of natural mortality, M, and of stock migration. Such errors will bias the estimates. This would also be the effect of a bias in the catch data, e.g. underreporting of catches.

For the Barents Sea capelin, where the acoustic technique has been most extensively used, no reliable VPAs or other measures of stock size exist. In such a case, only the consistency in the acoustic estimates between surveys or years can be analysed. Such analysis gives an idea about the variance on the estimates, while large systematic errors may exist without being discovered.

2. ACOUSTIC ESTIMATES

2.1 North-east arctic cod and haddock (Tables 1-3)

Since 1976 acoustic surveys have been carried out in the Barents Sea in order to estimate the abundance of demersal fish (Dalen and Smedstad, 1979). The main objectives of these investigations have been to obtain estimates of young cod and haddock. Dalen and Smedstad (1979) have given a detailed description of these cruises; the design, instrumentation, sampling and data analyzing procedures. In 1981 two commercial trawlers were used in addition to the research vessel in order to increase the number of trawling stations.

The yearly results of the cruises are given as number of individuals in each age group for all age groups of cod and haddock observed in the investigated area. Cod and haddock reach maturity at an age of 7-8 and 6 years respectively. The bulk of mature fish of both species will be on spawning migration during the period of investigation (February-March) and therefore mainly being distributed outside the area of investigation. Consequently the estimates of the adult age groups will only amount to a fraction of the "true" numbers, and are therefore excluded from the present analysis.

Two years, 1976 and 1980, have not been considered in this paper. In 1976 the survey coverage of the young fish distribution area was incomplete, and in 1980 the integration system worked unsatisfactorily. The results from the remaining years are shown in Table 1 and 2 for cod and haddock respectively. It should be noted that the 1981 VPA ("true" values) was calibrated to the results of the 1981 acoustic survey for cod but not for haddock.

Table 1 shows clearly that all age groups of young cod have been underestimated in the acoustic surveys each year although the variation from age group to age group is large. The percentage underestimation tend to be highest for the less numerous age groups, while the 1975 year class which is the most abundant year class throughout the period, seems to be less underestimated. The total stock of young cod were underestimated by 25-48 percent in the acoustic surveys in 1977-1979.

In Table 2 a similar presentation is given for haddock. As for cod the variation in errors from age group to age group is large, but generally the acoustic surveys have overestimated the numbers of haddock; the total stock of young fish being estimated to about twice the "true" value in 1977 and 1978.

Young cod and haddock will to a large extent occur together in the catches. The same age groups of the two species have also nearly equal sizes up to an age of 5 years. Therefore it might be convenient to consider the sum of cod and haddock in each age group. This is done in Table 3. Still there is a rather large variance between different age groups, but the large systematic errors which were experienced when considering the two species separately, have disappeared. The total stock of 2-5 years old fish seems to have been very precisely estimated acoustically all the years, except in 1979 when it is underestimated by approximately 30 per cent. The "true" 1979 stock depends, however, critically on the VPA input.

Why have the acoustic surveys resulted in an underestimation of cod and an overestimation of haddock? In our opinion the main reason must be sought in the representativity of the trawl catches. It has been assumed (Dalen and Smedstad, 1979) that the trawl catches reflect the true species and length (age) composition of the acoustically measured population. Judging from the results obtained above, this assumption has hardly been met.

The relative large error of 32 per cent underestimation in 1979 also needs some comments. During that winter a severe cooling of water masses took place in the area of investigation which lead to a westward displacement of the young fish from 1978 to 1979 (Midttun, Nakken and Raknes, 1981). It is thus possible that fish concentrations in the western Barents Sea were not covered satisfactorily by the 1979-survey.

2.2 Barents Sea Capelin (Table 4)

The stock of Barents Sea Capelin has been assessed on the basis of annual acoustic surveys since 1971 (Nakken and Dommasnes, 1977; Dommasnes, 1981). Capelin has a short life span. Most of the Barents Sea stock spawn at an age of 4 years along the northern coasts of Norway and the USSR in March-April. The acoustic survey, which since 1975 has been a joint Norwegian-USSR survey, is undertaken each year in September-October. All age groups are covered by the survey, but due to the behaviour patterns of 0- and I-group fish and because of different trawl selectivity of these two age groups as compared to larger fish, these age groups are excluded from the estimates (Nakken and Dommasnes, 1975 and 1977; Dommasnes, 1981). The results of the surveys are reported as number of individuals in each age group for fish which is 2 years and older.

Capelin suffers a mass mortality after its first spawning. Since most of the fish spawn at an age of 4 years and the first reliable estimate of a yearclass is obtained when the fish is 2 years old, an error analysis must be based on the comparison between the estimates of 2 and 3 years old fish in two successive years. Dommasnes (1981) has made such a comparison by estimating the natural mortality of capelin from 2 to 3 years

Table 1. North-east arctic cod. Number of individuals ($N \cdot 10^{7}$) in each age group estimated from acoustic survey each year and from virtual population analysis 1981 ("True" values) and percentage error.

	1977					1978						1979				1981				
	N_2	N_3	N_4	N_5	N_6	N_2	N_3	N_4	N_5	N_6	N_2	N_3	N_4	N_5	N_6	N_2	N_3	N_4	N_5	N_6
Acoustic estimates	88	10	32	14	5	24	80	15	17	3	1	11	50	8	5	7	6	12	24	27
"True" value	100	35	44	29	12	47	82	25	21	11	19	39	60	16	9	6	10	13	24	27
Per cent error	-13	-70	-28	-51	-56	-50	-2	-39	-17	-78	-93	-72	-16	-53	-50	+11	-42	-2	+2	0

Sum of 5 age groups	1977	1978	1979	1981
Acoustic estimate	149	139	75	76
"True" value	221	186	143	80
Per cent error	-33	-25	-48	-5

Sources: ICES C.M. 1982/G:2, Dalen and Smedstad (1979).

Table 2. North-east arctic haddock. Number of individuals ($N \cdot 10^{-7}$) in each age group estimated from acoustic surveys each year and from virtual population analysis 1981 ("True" values) and percentage error.

	1977				1978				1979				1981			
	N_2	N_3	N_4	N_5	N_2	N_3	N_4	N_5	N_2	N_3	N_4	N_5	N_2	N_3	N_4	N_5
Acoustic estimate	76	20	6	1	15	74	6	+	1	18	25	1	3	1	7	16
"True" value	28	12	4	2	20	26	5	1	6	16	13	2	10	5	4	8
Per cent error	+169	+71	+71	-33	-27	+185	+22	-89	-82	+10	+90	-35	-75	-72	+61	+105

Sum of 4 age groups	1977	1978	1979	1981
Acoustic estimate	103	96	45	27
"True" value	46	52	37	27
Per cent error	+124	+85	+22	0

Sources: As for Table 1.

Table 3. North-east arctic cod and haddock. Number of individuals ($N \cdot 10^{-7}$) in each age group estimated from acoustic surveys each year and from virtual population analysis in 1981 ("True" values) and percentage error.

	1977				1978				1979				1981			
	N_2	N_3	N_4	N_5	N_2	N_3	N_4	N_5	N_2	N_3	N_4	N_5	N_2	N_3	N_4	N_5
Acoustic estimates	164	30	38	15	38	153	21	17	3	29	75	9	10	7	19	40
"True" value	129	46	47	30	68	108	29	22	25	55	73	18	17	15	17	32
Per cent error	+27	-35	-21	-51	-43	+42	-29	-20	-90	-47	+3	-51	-41	-52	+14	+28

Sum of 4 age groups	1977	1978	1979	1981
Acoustic estimate	247	229	116	76
"True" values	252	227	171	81
Per cent error	-2	+1	-32	-6

of age. He arrived at estimates of natural mortality, M, between 0.35 and 1.03, most of the estimates being within the range, 0.6-0.7. The ICES working group has used a monthly natural mortality of 0.05 in the assessment of the stock. In the present paper we have adopted a constant natural mortality of 0.05 per month for the entire period between two surveys. Using this value and the catch in number by age data we have calculated the expected number of 3 year old fish from the observed number of 2 year old fish the previous year. The results are given in table 4. The deviations are the differences between the acoustically measured and the expected number of 3 year old fish.

Table 4 shows no systematic trend but large variances appear between different years (yearclasses); the deviations varying from +51 per cent to -71 per cent. However, in 5 of the 10 years the survey has been carried out, the deviations are less than 11 per cent, and these small discrepancies might probably be within the variations in the natural mortalities. The deviations of 30-50 per cent which occurred in 1978, 1979 and 1981 can probably not be explained by variations in natural mortality. For these years the sources of errors should be sought in the survey methodology and design, in the performance of the integration system or in the scattering cross sections which have been applied.

Table 4. Estimates of number of Barents Sea capelin ($N \cdot 10^{-9}$).

Year of observation:	1971	1972	1973	1974	1875	1876	1877	1978	1979	1980	1981
Acoustic estimates 2 years old fish	220	141	240	550	361	241	181	371	334	199	195
No. of months between surveys		10	14	12	12	12	12	12	12	12	12
No. of 3 year old fish estimated from $N_{t+1} = N_t \cdot e^{-M}$, M = 0.05 per month		133	86	132	301	198	132	99	204	183	109
Catch of year class between surveys		0	(18)	13	28	24	37	33	36	31	(30)
Expected no. of 3 year old fish		133	68	119	273	174	95	66	168	152	69
Acoustic estimate of 3 year old fish		140	20	160	304	167	102	100	113	154	48
Per cent deviation		+5	-71	+34	+11	-4	+7	+51	-32	+1	-31

Numbers in brackets are stipulated. The catch is mainly taken at the end of the period.
Sources: Nakken and Dommasnes (1977). Dommasnes (1981).

Table 4 may give the impression that systematic errors have been small and negligible, but this is not necessarily true. Since the annual total catches only amount to 12-30 per cent of the yearly reduction of a year class, the estimates of abundance may be scaled up or down without influencing the computed deviations significantly. Consequently, systematic errors, for instance caused by the application of too low or too high scattering cross sections, cannot be detected in the present analysis. However, comparison of acoustic estimates of the spawning stock of capelin with estimates obtained from tagging experiments and eggs and larvae surveys for the period 1972-1975 (Ulltang, 1977), indicated that no large systematic errors occurred during that period.

In some of the years incomplete area coverage might have been a significant source of error. In 1979 the lack of 3 year old fish in the acoustic survey was probably caused by insufficient coverage of the south easternmost areas of the Barents Sea.

3. ESTIMATES BY OTHER ASSESSMENT METHODS

In this section stock size estimates for each year during the period 1975-1978 as given in ICES Working Group reports the next year are compared with estimates of stock size for the same years as given in the VPA's carried out during the 1981 round of working group meetings. The latter ones are for convenience called "true" values. It should, however, be noted that:

1) The final year in these VPA's is 1980. Therefore, the estimate for 1978 is based on only 3 years catch data and may still be somewhat dependent on input fishing mortality or stock size for 1980. The likely errors from this source will decrease as one goes back to 1977, 1976 and 1975.

2) Disregarding the effect of wrong input values in 1980, the "true" values should rather be read as "the best estimate consistent with the value of natural mortality assumed in the VPA".

The comparisons have been carried out for the following stocks: North-east arctic cod, haddock and saithe, the North Sea and Western stock of mackerel, and North Sea cod.

A variety of data have been used in the assessments: Commercial catch per unit of effort data (cod, haddock and saithe), young fish trawl survey data (cod and haddock), data from egg surveys (mackerel) and tagging results (mackerel).

Before discussing the results it should be pointed out that the only objective of the present work is to illustrate the problems and likely size of errors connected with the various assessment methods. It has neither been possible nor attempted to fully reflect the discussion and possible reservations to the estimates given in the various Working Group reports.

Data on catch in number by age have been an essential part of the input in all the assessments discussed. For all stocks have been stated the kind of additional data which were utilized without repeating the existence of the basic data on catches and age compositions.

3.1 North-east arctic cod (Table 5).

The north-east arctic cod is entering the fishery in significant numbers as 3 years old. It recruits to the spawning stock at an age of about 8 years. Most of the catch of young immature cod is taken in trawl fisheries while a significant part of the catch of older fish is taken by other gears.

The data used by the Working Group over the period considered were mainly catch per unit of effort (CPUE) in various trawl fisheries, CPUE in the spawning fishery with long line, hand line and gill net, and abundance indices from pre-recruit trawl surveys.

Table 5 shows that the mature stock (N_{8+}) has been fairly accurately estimated over the whole period considered. However, great difficulties have apparently been experienced in estimating the younger part of the stock. Errors were consistently positive except in the 1979 assessment (1978 stock). For 1975-1976 the average exploitation pattern for the years 1970-1974 was assumed, which in retrospective can be seen resulted in too high stock sizes for the younger age groups, especially in 1976.

In the 1978 and 1979 reports, the Working Group did not assume an average exploitation pattern but studied in more detail CPUE-data from the various fisheries. By this procedure, fishing mortality was estimated separately for the younger and older component of the stock, and for the younger part the fishing mortality was estimated separately for each age group. The more detailed analysis of the CPUE-data seemed to improve significantly the estimates of 5 years old and older cod, but great difficulties were still experienced in estimating the number of 3 and 4 year olds, i.e. cod which have been in the fishery for only 1 or 2 years.

It should be noted that doubts have been expressed about the validity of the data on catch in number by age in 1978. Errors in those data would invalidate both the 1979 assessment and 1981 assessment of especially the 1978 stock.

3.2 North-east arctic haddock (Table 6).

Also the haddock is recruiting to the fishery in significant number as 3 years old. The spawning stock consists of 6 years old and older fish. Assessments for the years 1975-1978 were mainly based on CPUE-data from trawl fisheries and abundance indices from pre- recruit trawl surveys.

Errors in spawning stock estimates are somewhat larger than for cod probably since there is no separate spawning fishery for haddock with an extensive data base as it is for cod. Also for the younger age groups the errors are larger for haddock than for cod.

In contrast to the cod assessments, the Working Group continued to use the average exploitation pattern for the years 1970-1974 over the whole period, resulting in large errors in the assessment of the 1977 stock in 1978.

The comment made about 1978 catch data for cod concerns haddock as well.

In the preceding discussion emphasis has been laid on the difficulties arising from changing exploitation pattern. Such difficulties can to a large extent be overcome if catch per unit of effort data are broken down on age groups provided the appropriate data base for doing this exists. The large errors in especially the 1976 stock estimate for cod and the 1975-1977 stock estimates for haddock should therefore not be taken as estimates of likely errors when making optimal use of CPUE-data covering the main fisheries.

3.3 North-east arctic saithe (Table 7)

The saithe recruits to the fishery in significant number as 2 years old. The spawning stock consists of 6 years old and older saithe. There are two distinct main fisheries, a purse seine fishery which mainly exploits 2-4 years old fish and a trawl fishery where 4 years old and older fish predominate.

Assessments have generally been made by making judgments about changes in fishing effort in the different fisheries and selecting values of fishing mortality for the last year on the different age groups which in the VPA-output values gave trends which were in agreement with these changes. Details on this procedure are not given in the Working Group reports, and it is not known what data the judgments about changes in fishing effort really were based on.

Except for the 5 years old in 1976 and 4 years old in 1977, the errors are relatively small. This can probably be explained by the fact that the changes in effort over the period considered and the immediate preceeding years have been small, except for a drop in fishing effort in the trawl fishery in 1977 as a result of extended coastal state jurisdiction. The working group was able to take account of that in its assessment of the 1977 stock in 1978, but had apparently some problems with the 4 years old which according to the 1981 VPA were not affected by the drop in trawl effort.

The problem of measuring effective purse seine effort is wellknown. Since the fishing mortality on younger age groups of saithe mainly is generated by the purse seine fleet, and since in addition the purse seine effort may affect the various age groups differently in different years, depending on the geographical and seasonal distribution of the fishery, large errors could be expected in assessment of the younger age groups by the method used by the Working Group. Indeed, except for the two cases mentioned above, the authors found the errors surprisingly small.

3.4 North Sea cod (Table 8)

North Sea cod recruits to the fishery as 1 year old and to the spawning stock mainly as 3 years old. In its assessments the Working Group has used abundance indices from young fish trawl surveys and CPUE-data from the commercial fishery. Values of fishing mortality the most recent year have been selected to give VPAs

Table 5. North-east arctic cod. Stock size ($N \cdot 10^{-6}$) year t as estimated by Working Group year t + 1 (WG estimate), corresponding estimate from 1981 VPA ("True" value) and per cent "error".

	1975						1976					
	N_3	N_4	N_5	N_6	N_7	N_{8+}	N_3	N_4	N_5	N_6	N_7	N_{8+}
WG estimate	1048	426	778	336	78	38	1384	761	370	448	167	46
"True" value	629	351	620	256	64	36	627	474	234	305	104	41
Per cent "error"	+67	+21	+25	+31	+22	+6	+121	+61	+58	+47	+61	+12

	1977						1978					
	N_3	N_4	N_5	N_6	N_7	N_{8+}	N_3	N_4	N_5	N_6	N_7	N_{8+}
WG estimate	419	708	339	119	121	58	476	193	245	135	56	98
"True" value	348	437	286	120	144	58	816	249	207	112	51	81
Per cent "error"	+20	+62	+19	-1	-16	0	-42	-22	+18	+21	+10	+21

Sources: ICES C.M: 1976/F:10, 1977/F:6, 1978/G:64 Revised, 1979/G:20, 1982/G:2

Table 6. North-east arctic haddock. Stock size ($N \cdot 10^{-6}$) year t as estimated by Working Group year t + 1 (WG estimate), corresponding estimate from 1981 VPA ("True" value) and per cent "error".

	1975				1976			
	N_3	N_4	N_5	N_{6+}	N_3	N_4	N_5	N_{6+}
WG estimate	108	46	73	109	150	55	17	168
"True" value	51	36	100	170	58	33	17	142
Per cent "error"	+112	+28	-27	-36	+159	+67	0	+18

	1977				1978			
	N_3	N_4	N_5	N_{6+}	N_3	N_4	N_5	N_{6+}
WG estimate	339	78	19	77	193	45	7	28
"True" value	116	35	15	66	257 1)	45	9	39
Per cent "error"	+192	-123	+27	+17	-25	0	-22	-28

1) Based on revised VPA, ACFM November 1981.
Sources: ICES C.M: 1976/F:10, 1977/F:6, 1978/G:64 Revised, 1979/G:20, 1982/G:2

Table 7. North-east arctic saithe. Stock size (N·10-6) year t as estimated by Working Group year t + 1 (WG estimate), corresponding estimate from 1981 VPA ("True" value) and per cent "error"

	1975					1976				
	N_2	N_3	N_4	N_5	N_{6+}	N_2	N_3	N_4	N_5	N_{6+}
WG estimate	455	141	41	81	121	308	273	85	30	85
"True" value	404	177	35	60	100	378	257	91	18	91
Per cent "error"	+13	-20	+17	+35	+21	-19	+6	-7	+67	-7

	1977					1978				
	N_2	N_3	N_4	N_5	N_{6+}	N_2	N_3	N_4	N_5	N_{6+}
WG estimate	142	290	158	46	61	264	104	88	61	56
"True" value	194	261	99	47	62	287	131	125	50	71
Per cent "error"	-27	+11	+60	-2	-2	-8	-21	-30	+22	-21

Sources: ICES: C.M.: 1976/F:2, 1977/F:3, 1978/G:3, 1979/G:6

consistent with calculated trends in effort. However, for all the years considered, except when estimating the 1975 stock in 1976, the fishing mortality on the 1-group has been adjusted to give year class strength consistent with the young fish trawl survey data.

The I-group has been fairly accurately estimated over the period, while some rather large overestimates are found for the 2-group.

3.5 North Sea mackerel (Table 9)

North Sea mackerel recruits to the fishery at an age of 2 years and to the spawning stock at age 3.

Assessments have almost entirely been based on tag recaptures. Egg surveys to monitor changes in the spawning stock have been carried out since 1973, but data from these have only been used as supporting evidence for estimated trends in spawning stock from VPAs where the input fishing mortalities have been based on tagging results. Since the tag recaptures give no estimates for the youngest age groups, these have been estimated by assuming certain relative values of fishing mortality compared to the older ones.

Some reservations should be made to the estimated "errors" in Table 10.

1) North Sea and Western mackerel are during summer mixed in feeding areas in the northern North Sea. Catches have been allocated to stocks by utilizing tagging data, but large uncertainties exist in the estimated proportions. VPA estimated stock sizes backwards are valid only as far as the allocation of catches to stocks are valid. Therefore the term "true" stock is even more obscure in this case.

2) Tag recaptures from 1979 onwards have been too few to give a valid estimate of fishing mortality in 1979 or 1980. The fishing mortalities for 1980 in the last VPA were selected to give values for previous years similar to those estimated by the 1979 Working Group. The small "error" in the 1978 stock estimate of ages 3 and older therefore only reflects the calibration of the 1981 assessment to the 1979 assessment.

3) The analysis for 1975 and 1976 was based on values of natural mortality, M=0.2, while in subsequent years M=0.15 was used in accordance with estimates from tagging data.

Having made these reservations, it should be noted that the estimated errors of the 3+ stock were small also in 1977 and 1975. The error in 1976 was larger, +44 per cent. The working group says in its 1978 report that some overestimation had taken place because wrong proportions of catches were allocated to the North Sea stock for 1976 at the 1977 meeting.

It appears that the number of 2 years old fish has been significantly underestimated in three of the years.

3.6 Western mackerel (Table 10)

The Western mackerel recruits to the fishery in significant numbers already as 1 year old, and to the spawning stock as 3 year old.

In the assessment of the 1975 and 1976 stock in 1976 and 1977 respectively, terminal fishing mortalities and resulting stock sizes of one particular year class, the 1969 year class, were estimated from North Sea tagging data, assuming that the proportions of this year class from the two stocks in the mixing area around Shetland reflected its strength in the two stocks. The other year classes were then estimated from assumed relative values of fishing mortality. It is seen that this resulted in underestimation of the adult stock of Western mackerel in both years.

Table 8. North Sea cod. Stock size ($N \cdot 10^{-6}$) year t as estimated by Working Group year t + 1 (W.G. estimate), corresponding estimate from 1981 VPA ("true" value) and per cent "error".

	1975			1976			1977			1978		
	N_1	N_2	N_{3+}	N_1	N_2	N_{3+}	N_1	N_2	N_{3+}	N_1	N_2	N_{3+}
WG Estimate	196	99	98	119	284	109	273	94	58	163	378	65
"True" value	226	93	64	110	158	58	386	84	68	233	262	53
Per cent "error"	-13	+7	+53	+8	+80	+88	-29	+12	-15	-30	+44	+23

Sources: ICES C.M.: 1976/F:9, 1977/F:8, 1978/G:7, 1979/G:7
Working Document, ACFM Nov. 1981.

Table 9. North Sea mackerel. Stock size ($N \cdot 10^{-6}$) year t as estimated by Working Group year t + 1 (W.G. estimate), corresponding estimate from 1981 VPA ("true" value) and per cent "error".

	1975		1976		1977		1978	
	N_2	N_{3+}	N_2	N_{3+}	N_2	N_{3+}	N_2	N_{3+}
WG estimate	80	2504	819	2784	141	1605	72	1350
"True" value	444	2305	548	1933	313	1796	137	1481
Per cent "error"	-82	+9	+50	+44	-55	-11	-47	-9

Sources: ICES C.M.: 1976/H:3, 1977/H:2, 1978/H:4, 1979/H:3, 1981/H:7

Table 10. Mackerel, Western stock. Stock size ($N \cdot 10^{-6}$) year t as estimated by Working Group year t + 1 (W.G. estimate), corresponding estimate from 1981 VPA ("True" value) and per cent "error".

	1975			1876			1977			1978		
	N_1	N_2	N_{3+}	N_1	N_2	N_{3+}	N_1	N_2	N_{3+}	N_1	N_2	N_{3+}
WG estimate	192	1521	6145	4143	1877	5419	4000	6093	8974	517	3642	9699
"True" value	2619	3034	11638	4021	2205	10442	4217	3202	9952	531	4387	9625
Per cent "error"	-93	-50	-47	+3	-15	-48	-5	+90	-10	-3	+4	+1

Sources: ICES C.M.: 1976/H:3, 1977/H:2, 1978/H:4, 1979/H:3, 1981/H:7

The problem of allocating catches to stock in the mixing area also have consequences for assessment of the Western mackerel, especially when using the method described above. Thus, the wrong allocation of 1976 catches to stock which led to overestimation of the North Sea stock in 1976 contributed to the underestimation of the Western stock.

In 1977 a large scale egg survey was carried out, and the spawning stock in 1977 was calculated from that survey. Also the spawning stock in subsequent years was indirectly estimated from that survey by calibration of the VPA to give a backcalculated 1977 stock equal to the survey estimate. The VPA carried out in 1981 was calibrated to a new egg survey carried out in 1980. The results indicate that such large scale egg surveys can give rather precise estimates. The main problem in the Western stock assessment, as for the North Sea stock, seems to be the estimation of younger age groups where changes in relative fishing mortalities from year to year may heavily bias the results.

By basing the assessment of the Western stock on the egg surveys, errors in assessment arising from uncertainties in allocation of catches to stock in the mixing area have been strongly reduced since most of the western mackerel is caught in other areas.

4. DISCUSSION AND CONCLUSIONS

In Fig. 1a is the percentage error in the VPA-assessments of total young fish stock and adult stock plotted for the four demersal stocks while Fig. 1b shows the percentage error in the acoustic estimates of the young fish stocks of N-E arctic cod and haddock and for the total of the two species. Considering N-E arctic cod and haddock it is seen that large problems have been experienced by both methods in the assessment of the young fish stocks. Yet, when grouping cod and haddock the acoustic results are surprisingly good. Thus it might be concluded that the acoustic surveys seem to produce fairly reliable information about the state of the total young fish stock of cod and haddock in the Barents Sea.

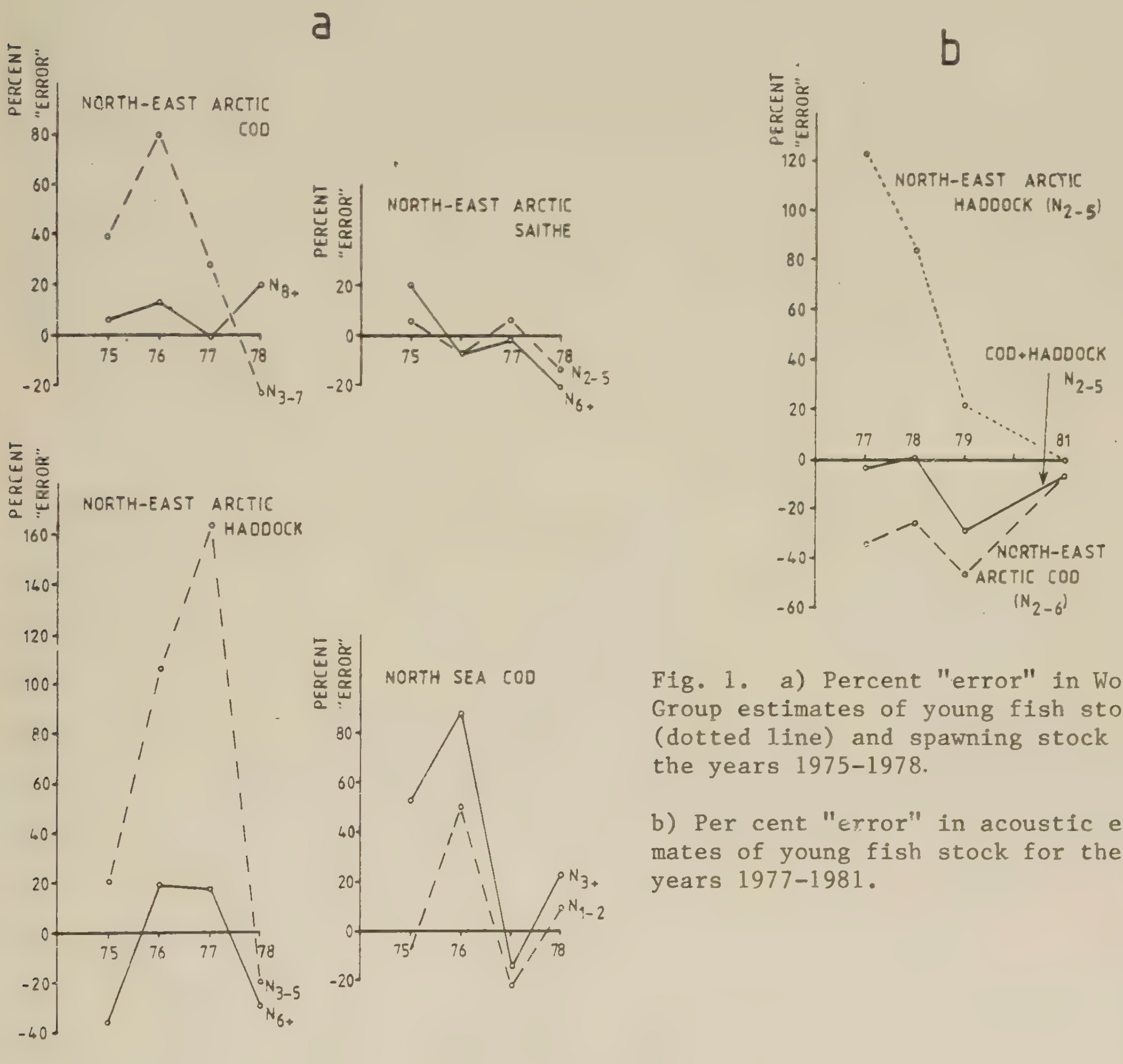

Fig. 1. a) Percent "error" in Working Group estimates of young fish stock (dotted line) and spawning stock for the years 1975-1978.

b) Per cent "error" in acoustic estimates of young fish stock for the years 1977-1981.

From Fig. 1 it is also seen that the VPA-assessments of the adult stock of N-E arctic cod and haddock have been more precise than for the young fish stock and regarding N-E arctic saithe and North Sea cod the errors seem to be of about the same level for the two components. It should, however, be pointed out that for predictive purposes a much higher precision may be required for the assessment of the young fish stock than for the adult stock.

The errors in the acoustic estimates of Barents Sea capelin have varied considerably over the period. Yet, on an average, the number of capelin seem to have been estimated acoustically with a precision comparable to that for the young fish stocks of N-E arctic cod and haddock when these two species are grouped. The lack of other measures of capelin abundance precludes an evaluation of the accuracy of the acoustic estimates.

For the two mackerel stocks, disregarding the years 1975-1976 for the western stock, the adult stocks have been estimated with rather high precision while the results for the younger age groups are more variable. This is not surprising since the adult stocks have been estimated from tagging experiments and egg surveys while the younger age groups have been estimated by making assumptions on fishing pattern.

It is of course impossible from the analysis carried out in this paper to rank one assessment method above the other, in general. Each method has its strength and weaknesses depending on the behaviour, availability to gears and instruments and migration patterns of the fish stock in question. Further, limitations of man power as well as limitations due to vessel and instrument costs will highly influence the results obtained by any assessment method. However, judging from the results presented here it seems that abundance estimates from acoustic surveys have reached a precision and accuracy which significantly could improve the assessment of some fish stocks or stock components which previously, with large errors, have been assessed mainly by fishery dependent data and methods.

SCALING OF AN ECHO INTEGRATOR USING ECHO COUNTS, AND A COMPARISON OF ACOUSTIC AND WEIR COUNT ESTIMATES OF A JUVENILE SOCKEYE SALMON POPULATION

BY

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ABSTRACT

An investigation of an echo count-echo integration regression method of scaling echo integrator data was conducted to provide information on the reliability of the method. The research included application of the method on the series of acoustic surveys used to estimate the abundance of juvenile sockeye salmon (Oncorhynchus nerka) in Cultus Lake, British Columbia, and a comparison of the survey population estimate with an independent estimate determined from enumeration of downstream migrants at the outlet of the lake. A simulation analysis of the sampling volume estimation method used to derive fish density was also completed. The close agreement of the echo integration and direct sampling estimates indicated the surveys were capable of providing an accurate estimate of the population of salmon which migrated out of the lake.

RESUME

Une investigation d'une méthode pour étalonner les données d'intégrateur d'échos par moyen du comptage des échos et de la régression de l'intégrateur d'échos a été conduite en vue de fournir des renseignements sur la précision de cette méthode. Les recherches ont compris l'application de cette méthode à une série de sondages acoustiques utilisés pour estimer l'abondance de juvéniles du saumon nerka (*Oncorhynchus nerka*) dans le lac Cultus de la Colombie Britannique. Elles ont également inclus une comparaison de l'estimation de stock dérivée de ce sondage avec une estimation indépendante déterminée par le dénombrement des poissons migrateurs retrouvés en aval à la sortie du lac. Une analyse simulatrice de la méthode d'estimation basée sur le volume d'échantillonnage utilisée pour déterminer la densité de poissons a été également mise au point. L'accord étroit entre les données rendues par l'intégration d'échos et celles dérivées des estimations d'échantillonnage direct a indiqué que les sondages ont été capables de fournir une estimation bien précise du nombre de poissons qui avaient quitté le lac.

1. INTRODUCTION

During the early 1970's, many acoustic surveys of the distribution and abundance of juvenile sockeye salmon (Oncorhynchus nerka) and other fishes were conducted in Washington, Alaska, and British Columbia lakes. Estimates of population size were frequently determined using uncalibrated (except for receiver gain) echo sounders and a digital echo integrator (Nunnallee, 1973; Thorne, 1973). Calibration measurements (source level, receiving sensitivity) and fish target strength data were generally not available so most investigators converted the integrator outputs to estimates of density using echo count-echo integration regression relationships established from data obtained in situations where single fish echo counting was possible (Croker, 1972; Lemberg and Mathisen, 1975; Nunnallee and Mathisen, 1972; Traynor, 1973).

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[1] The research reported in this paper was conducted while the author was employed by the Fisheries Research Institute, University of Washington, Seattle, Wash.

An investigation of the echo count- echo integration regression method of echo integration scaling was conducted by Nunnallee (1980). This involved application of the method on a series of surveys conducted to estimate the juvenile sockeye salmon population in Cultus Lake, British Columbia, and a comparison of the survey population estimate with that determined from direct enumeration of downstream migrants. It also included a computer simulation analysis designed to provide information on the relative effect of different sources of bias in the echo counting procedure. This report provides a summary of the results of the research.

2. SURVEY AREA AND METHODS

Cultus Lake is a relatively small (6.3 km^2) oligotrophic lake located in southwest British Columbia about 60 miles from the Pacific Ocean. It has a steep-sided basin with a maximum depth of 40 m. Sweltzer Creek, the outlet stream, flows into the Frazer River.

Research on the lake's sockeye salmon population has been conducted continuously for over 40 years. Essentially all sockeye salmon in each year class migrate to sea at age 1 (length, 60-100 mm). The smolt migration begins about 1 April and is normally completed by early May, prior to the time when significant numbers of young-of-the-year sockeye appear in the limnetic area of the lake. Other species in the lake include threespine stickleback (Gasterosteus aculeatus), northern squawfish (Ptychocheilus oregonensis), large scale sucker (Catostomus macrocheilus), cutthroat trout (Salmo clarki), Dolly Varden (Salvelinus malma), and coho salmon (Oncorhynchus kisutch). The combined population of these fishes is relatively small compared to the juvenile sockeye population.

Nine acoustic surveys were conducted in the spring of 1977, each run on the same set of transects (Fig. 1) at a boat speed of about 4 m/sec. The first survey (16 March) was conducted about 3 weeks prior to the beginning of the smolt migration, the next seven at approximate 1 week intervals between 4 April and 17 May, and the last on 6 June. Each included 1 or 2 replicates. Twenty population estimates were made for the overall survey series. All surveys were run at night when the juvenile sockeye were distributed in the upper part of the water column, mainly 20-25 m. During the day they were schooled on or near bottom. To compensate for the presence of non-sockeye, the size of the juvenile population in the lake was estimated from the acoustic surveys as the difference between the 16 March survey estimate and that determined during the 2 May series. By 2 May the smolt migration was essentially completed.

Acoustic data were collected using a 105 kHz echo sounder equipped with a circular transducer having a 10^o (-3dB, full angle) beam pattern. Echo data were recorded on magnetic tape in the field. The transmitted pulse length was 0.7 ms and the sounder's ping rate was 2/sec. A highly stable calibration oscillator was installed in the sounder to provide a means of monitoring changes in receiver gain. Test signals could be coupled to the receiver input by depressing a front panel switch.

All the tape recorded data were returned to the laboratory for analysis. The digital echo integrator was capable of processing data in up to nine contiguous depth intervals for any desired time pariod (number of pings). An 8 bit A-D converter at the input of the integrator had a 0.2 V threshold and a 10 V maximum input level and, therefore, the analog input dynamic range was limited to 34 dB. Voltage squaring was done by a 12-bit digital module.

The population of migrating smolts was enumerated as it passed through a weir built across Sweltzer Creek near the outlet of the lake. The weir was operated continuously throughout the migration period (7 April - 13 May) by the International Pacific Salmon Fisheries Commission. The number of smolts passing through the weir each day was estimated by expansion of the numbers of fish in samples captured in an automatic sampling device (Davis and Hiltz, 1971). The proportionality constant of the device was estimated on four occasions during the migration by capturing all of the fish passing through the weir.

3. ECHO INTEGRATION SCALING AND POPULATION ESTIMATION

Fish density estimates were determined from the acoustic data from each survey series, using the following procedures. First, using the echo counting method described below, an estimate of fish density was calculated for each of several samples of data for each (5 m) depth stratum of interest. Echo integrator outputs for each counted sample were then obtained using integrator scaling coefficients of 1.0. Finally, for each depth stratum, the count-estimated densities were regressed on the integration values. The remainder of the survey data was then processed with the echo integrator and converted to estimates of density (fish/m^3) using the regression coefficient as the scaler. Care was taken in the selection of echo data to avoid areas having multiple (overlapping) fish detections.

3.1 Echo Counting Method

The sampling volume of the echo sounder beam for each depth stratum was estimated as the volume of the frustum of a right cone. This was calculated from the approximate formula, $V=r^2h$, where h is the height of the frustum (thickness of the depth stratum) and r is the radius of the beam at mid stratum depth. Estimation of beam radius was based on the average number of sequential detections per fish, ping rate, and boat speed. A detection was defined as a single fish echo voltage that exceeded a threshold level. Since the echo amplitude of an on-axis target decreased with range as $-20 \log_{10} R$ ($\alpha=0$ in fresh water), a threshold curve was calculated which followed the same function and was referenced to the minimum echo amplitude of interest at the maximum depth of data collection. The curve was adjusted for TVG error by measuring the internal calibration signal at the receiver output for a series of range increments. The threshold curve was calculated by,

$$E_t = K(E_o/E_e)/R$$

where K is a constant and, for any range R, E_t is threshold voltage, E_o is measured receiver output voltage, and E_e is the receiver output voltage for an ideal $20 \log_{10} R$ TVG function referenced to E_o at a reference depth. The constant, K, was calculated by setting E_o and E_e equal at the reference depth. A more detailed discussion of the counting threshold is presented by Nunnallee (1980).

After a counting threshold was calculated, it was scribed onto a piece of acetate which was placed over the screen of an oscilloscope. Recorded echo data were then displayed and counts were made of the numbers of detections of individual fish (detections/fish) within individual depth strata. This procedure was applied to a number of time segments within each depth stratum. The mean number of detections per fish for each stratum was then calculated. It was assumed that the fish were stationary while in the beam and that within each depth stratum they were randomly distributed.

The mid-depth radius, r, of the echo sounder beam for a depth stratum was calculated from an estimate of the average apparent path length (average chord length) described by a fish passing (due to boat movement) through the beam.

Average chord length, c, was calculated as,

c = (sec/ping) x (avg. no. detections/fish) x (boat speed; m/sec). Since,

$$\bar{c} = E(c) = \int_{-r}^{r} (r^2-x^2)^{1/2}dx = \pi r/2$$

then,

$$r = 2\bar{c}/\pi$$

which is the mid stratum radius of a conic frustrum, for which volume is calculated as indicated previously. Fish density (fish/m^3) is then calculated by,

$$\hat{\rho} = \frac{\text{total detections}}{(\text{vol/ping}) \times (\text{total pings})}$$

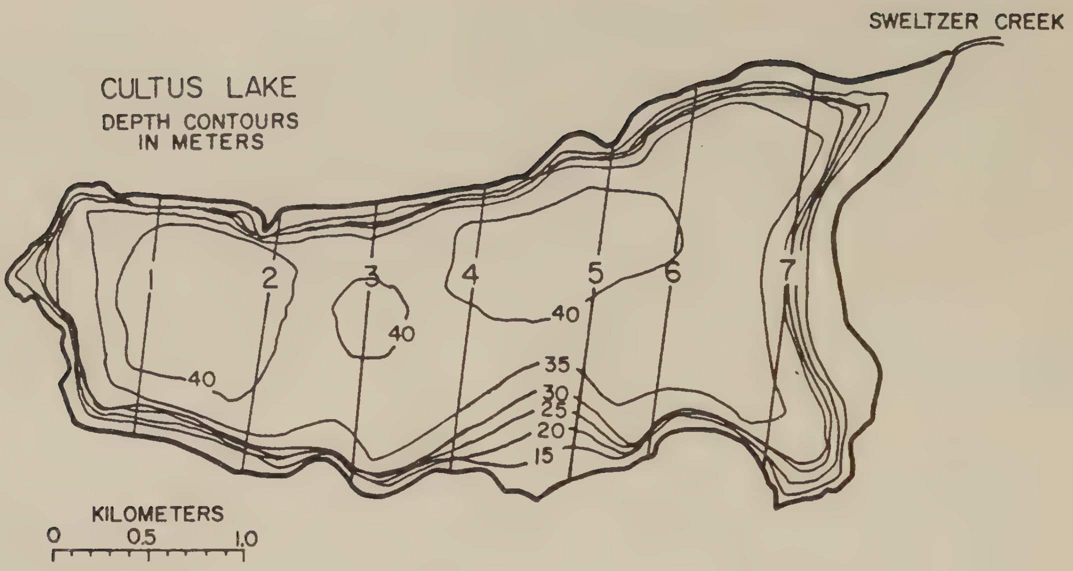

Fig. 1. Map of Cultus Lake showing location of acoustic survey transects.

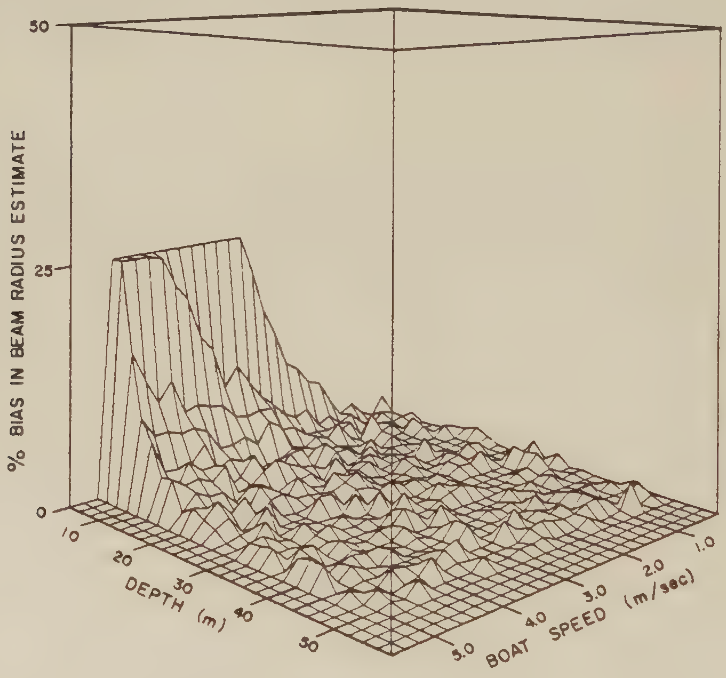

Fig. 2. Three dimensional plot of bias in beam radius estimates predicted by the simulation for the indicated ranges of boat speed and depth. Parameter estimates were: system dynamic range = -20 to -60 dB; target strength normally distributed with mean = -40 dB and S(TS) = 3dB; N = 1000 observations for each 0.5 m of depth and 0.2 m/sec increments of boat speed. Bias values greater than 25% were truncated for plotting convenience.

3.2 Sources of Bias in the Echo Counting Method

A computer program was written to simulate the operation of an acoustic data collection system and the detection counting method used to estimate beam dimensions and, hence, sampling volumes. A few results of the simulation are presented below. The purpose of the simulation was to estimate bias in sample volume estimation due to (1) interaction of boat speed, ping rate, and depth; (2) background noise level, dynamic range of the receiver, and transducer beam angle; (3) stratification of fish size by depth; and (4) target strength (size) distribution of the fish.

Simulation results indicated that stratification of fish size by depth and variation in the target strength distribution were the least significant sources of bias for the Cultus Lake surveys provided depth specific estimates were obtained, and no fish were detected in the side lobes of the beam pattern. The first side lobe of the transducer used during the Cultus Lake surveys was 15.5 dB below the main lobe, and it was apparent that side lobe detections occurred infrequently.

The simulation showed that errors in beam radius estimates could be very large for shallow depths when the number of detections per unit distance was relatively low, i.e., relatively high boat speed and/or low ping rate (Fig. 2). A general guide for maintaining the bias in sampling volume estimation to 2%, or less, as implied by the simulation results, is to keep $B \leqq 1.0$;

$$B = \frac{BS \times PR}{D \times \mathrm{Tan}(\theta)}$$

where BS= boat speed (m/sec), PR= ping rate (sec/ping), D= depth of analysis (m), θ= effective full beam angle (deg).

A bias level of approximately 5% occurs when B= 1.4 and about 25% when B= 4.0.

3.3 Fish Density and Population Estimation

As indicated earlier, for selected samples of echo data, estimates of absolute density determined by the counting method were regressed on relative densities (echo integration outputs) to provide scaling coefficients (slope and intercept coefficients) required to convert the survey integration data to estimates of fish density. The regression relationship was

$$\rho_D = \alpha_D + \beta_D I_D^*, \qquad (1)$$

where ρ_D is the count-derived density estimate, I_D^* is the corresponding integration value, and D refers to a specific 5 m depth stratum. A regression equation was determined for each 5 m depth stratum between 5 m and 40 m, for each of the nine survey periods. For population estimation, average density in each depth stratum was estimated by

$$\hat{\bar{\rho}}_D = \hat{\alpha}_D + \hat{\beta}_D \bar{I}_D, \qquad (2)$$

where $\bar{I}_D$ is the overall mean integration value for the stratum. This value was calculated from individual integrator outputs obtained at 5 minute (600 ping) intervals during each survey. An estimate of the variance of the mean density was determined using the method described by Traynor (1973). The variance estimator is

$$\mathrm{Var}\ (\hat{\bar{\rho}}_D) = \mathrm{Var}\ (\hat{\alpha}_D + \hat{\beta}_D \bar{I}_D) \qquad (3)$$

which can be rewritten as

$$\mathrm{Var}\ (\hat{\bar{\rho}}_D) = \mathrm{Var}\ (\hat{\alpha}_D) + \mathrm{Var}\ (\hat{\beta}_D \bar{I}_D) + 2\ \mathrm{Cov}\ (\hat{\alpha}_D, \hat{\beta}_D \bar{I}_D) \qquad (4)$$

If $\hat{\beta}_D$ and $\bar{I}_D$ are assumed to be independent, the second term of equation (4) can be expanded to

$$\mathrm{Var}\ (\hat{\beta}_D \bar{I}_D) = \mathrm{Var}\ (\bar{I}_D)\ (E(\hat{\beta}_D))^2 + \mathrm{Var}\ (\hat{\beta}_D)\ (E(\bar{I}_D))^2 + \mathrm{Var}\ (\bar{I}_D)\ \mathrm{Var}\ (\hat{\beta}_D) \qquad (5)$$

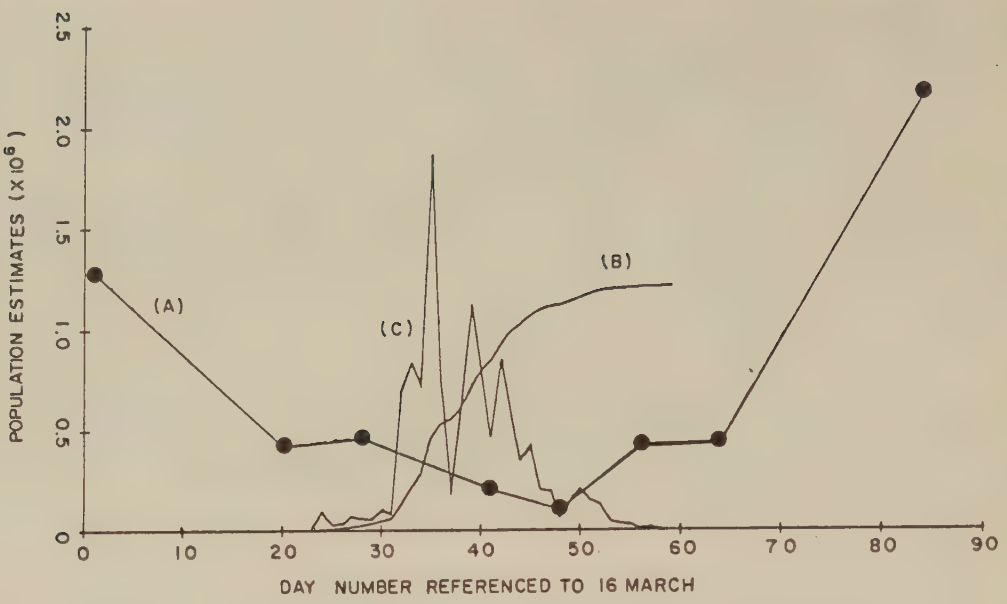

Fig. 3. Acoustic population point estimates by survey period (A), and cumulative (B) and daily (C) counts (X5) of sockeye salmon smolts at the Sweltzer Creek weir.

Table 1. Averages of acoustic estimates of total fish population size for each survey period.

Date	Day no.1/	Population estimate	
		Total no.	95% CI
16 March	1	1,280,398	178,720
4-5 April	20	424,058	120,990
12-13 April	28-29	458,535	52,715
19 April	35	2/	2/
25-26 April	41-42	204,847	78,618
2 May	48	104,486	24,721
9 May	56	418,516	128,688
17 May	64	432,702	116,329
6 June	84	2,140,959	858,137

1/ Relative to 16 March (Day 1).

2/ Data invalid due to malfunction of equipment during data collection.

Table 2. Counts of total numbers of sockeye smolts passed through the Sweltzer Creek weir and the percentage captured by the automatic sampling device.

Total fish passing weir	Number captured in automatic sampler	Percentage sampled 100 x (sample/total)
1,188	54	4.545
2,471	104	4.209
3,582	157	4.383
2,833	119	4.200
		X = 4.334
		S(X) = .00521

Let $Var(\bar{I}_D) = \sigma^2_D$, $E(\hat{\beta}_D) = \beta_D$, $E(\bar{I}_D) = \mu_D$ and N_D be the number of 5 minute samples of echo data used to estimate $\bar{I}_D$. Then $Var(\bar{I}_D) = \sigma^2_D/N_D$ and, by substitution into equation (5),

$$Var(\hat{\beta}_D\bar{I}_D) = \frac{\sigma^2_D}{N_D}(\hat{\beta}_D)^2 + Var(\hat{\beta}_D)\mu^2_D + \frac{\sigma^2_D}{N_D} Var(\hat{\beta}_D) \qquad (6)$$

The third term in equation (4) can be expressed as

$$2\ Cov(\hat{\alpha}_D, \hat{\beta}_D\bar{I}_D) = 2\ Cov(\hat{\alpha}_D, \hat{\beta}_D)\mu_D = 2\ \bar{I}_D{*}\mu_D\ Var(\hat{\beta}_D) \qquad (7)$$

since $I_D{*}$ is the mean integration value used in estimation of the regression coefficients. Substitution of equation (6) and (7) into equation (4) results in

$$Var(\hat{\rho}_D) = Var(\hat{\alpha}_D) + \frac{\sigma^2_D}{N_D}(\hat{\beta}_D)^2 + Var(\hat{\beta}_D)\mu^2_D + \frac{\sigma^2_D}{N_D} Var(\hat{\beta}_D)$$

$$- 2\bar{I}_D{*}\ \mu_D\ Var(\hat{\beta}_D) \qquad (8)$$

To estimate $Var(\hat{\bar{\rho}}_D)$, estimates of $Var(\hat{\alpha}_D)$, $\hat{\beta}_D$, and $Var(\hat{\beta}_D)$ were obtained from the regression analysis. Estimates of σ^2_D and μ_D were calculated from the total set of integration values for each depth stratum.

Population estimates for the lake were calculated, for each survey, by extrapolation of mean depth strata densities over corresponding strata volumes and then summing over all depths. Although the 0-5 m depth stratum could not be surveyed, it was assumed that the mean fish density and its variance in that stratum were the same as in the 5-10 m stratum. Because of the steep sides of the lake basin, the volumes of the 0-5 m and 5-10 m strata are essentially equal. Population estimates and confidence intervals by depth strata were estimated from

$$\hat{P}_D = \hat{\bar{\rho}}_D V_D \pm t_{(\alpha,\ n-1)} = \{Var(\hat{\bar{\rho}}_D)\}^{\frac{1}{2}} V_D \qquad (9)$$

where V_D is the volume of depth stratim D. Total population estimates were calculated from

$$\hat{P}_{lake} = \sum_{D=1}^{n} P_D$$

The confidence interval for this estimate was

$$CI_{lake} = \hat{P} \pm t_{(\alpha,N-n)} \{V_1^2\ Var(\hat{\bar{\rho}}_{D1}) + V_2^2\ Var(\hat{\bar{\rho}}_{D2}) +\text{----}+ V_n^2\ (\hat{\bar{\rho}}_{Dn})\}^{\frac{1}{2}} \qquad (10)$$

where $v_1, v_2 \ldots v_n$ = volumes of depth strata 1, 2...n, and N and n = total number of density estimates and number of depth strata, respectively.

Because differences between lake population estimates made within a survey period were small, an overall estimate for each survey period was calculated by averaging the individual estimates. The variance for each survey period estimate was calculated as

$$Var(\hat{\bar{P}}_{sp}) = \{\sum_{i=1}^{t} Var(\hat{P}_i)\}^{\frac{1}{2}} \qquad (11)$$

where Var $(\hat{P}_i)$ is the variance indicated within brackets in equation 10 and t is the number of surveys run during the period.

4. RESULTS AND DISCUSSION

The averages of total fish population estimates (all species) for each survey period are shown in Table 1. The population estimates declined significantly between 16 March and 2 May. After 2 May, the influx of young-of-the-year salmon fry obscured further observation of the effect of the outmigration of yearling salmon. The outmigrant population estimate, the difference between the 16 March (day 1) and 2 May (day 48) estimates, was 1,176,000. The confidence interval for this estimate was,

$$CI = V\ \{(\hat{\bar{\rho}}_1 - \hat{\bar{\rho}}_{48}) \pm t_{(\alpha,n)}(S_1^2+S_{48}^2)^{\frac{1}{2}}\} \qquad (12)$$

where S_1^2 and S_{48}^2 are the variances of the weighted mean fish densities for the two surveys. The estimated confidence interval was 942,000 to 1,410,000 fish; about ±20% of the population estimate.

Daily and cumulative daily counts of sockeye smolts estimated to have passed through the weir on Sweltzer Creek are shown in Fig. 3. The estimated total number of smolts was 1,204,000. The 95% confidence interval for this estimate was 1,058,000 to 1,349,000 fish (±12% of the point estimate). The confidence interval was estimated from data on the proportion of fish that was captured as the migrants passed through the automatic sampling device in the weir (Table 2).

The acoustic and weir estimates of the size of the juvenile sockeye salmon population were in close agreement. The acoustic estimate was only 2.5% less than the weir count estimate, and there was complete overlap of the 95% confidence intervals. The small difference in the estimates indicated that, for the Cultus Lake juvenile sockeye population, the two techniques are comparable, and both are capable of providing accurate estimates of abundance. If similar surveys were to be conducted in the future, it would be of value to further investigate the variance structure of the acoustic estimates, particularly since no attempt was made to correct for autocorrelation effects.

The feasibility of the acoustic survey technique and the ability to compare the two estimateion methods was largely a result of the behaviour of the juvenile sockeye. At night, after initially migrating upward to near the surface, the fish were relatively uniformly distributed in the upper half of the water column where they usually were detected as single targets. During the hours chosen for the surveys, they were most abundant at depths of 10 to 25 m and few were observed near the bottom. The relatively rapid (approximately 37 days) and well defined outmigration left little uncertainty as to when operations could be terminated without affecting the results (Fig. 3). Although enumeration at the weir continued until 13 May, it is reasonable to assume the sockeye population available to the acoustic survey was at a minimum on 2 May. Only 7% (82,000 fish) of the total weir count estimate occurred during 3-13 May and even most of these fish may not have contributed to the 2 May acoustic estimate. This is because, once the movement of fish our of the lake had begun, a portion of the outmigrant population was probably always near the outlet where it was not encountered by the acoustic survey. This phenomenon was most apparent at the beginning of the overall survey period, i.e., although smolts were not counted at the weir site until 7 April, the acoustic survey population estimate for the second (4-5 April) survey was 65% less than for the first (16 March).

It should be noted that, because of the freshwater life history of sockeye salmon in Cultus Lake, the present study provided a rare opportunity to compare an acoustic estimate of abundance with an independent estimate obtained by a very comparable direct estimation method.

APPLICATION OF HYDROACOUSTIC ASSESSMENT TECHNIQUES TO THREE LAKES WITH CONTRASTING FISH DISTRIBUTIONS

by

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ABSTRACT

Since 1969, the Fisheries Research Institute of the University of Washington has conducted over 200 hydroacoustic surveys on 25 different lakes using echo integration and echo counting techniques. This paper describes results of surveys on three lakes which typify the variety of these applications: Washington, Tustumena, and Twin Lakes. Nearly 100 hydroacoustic surveys have been conducted on Lake Washington including estimates of presmolt sockeye salmon for 12 years. These results have been used in the management of the sockeye salmon fishery and for evaluation of factors affecting productivity. Hydroacoustic estimates have compared well with estimates from midwater trawling. Lake Tustumena is also a sockeye salmon nursery lake, but much larger and with a more patchily distributed population, as well as distribution very near surface. Estimates in this lake have used a combination of downlooking and uplooking transducer deployments. Twin Lakes supports a lake trout population with much lower densities and even greater patchiness, which resulted in greater variability in the population estimates from the hydroacoustic surveys.

RESUME

Le Fisheries Research Institute of the University of Washington (l'Institut de recherche sur la pêche de l'Université de Washington) a, depuis 1969, conduit plus de 200 études hydroacoustiques sur 25 lacs en employant des techniques d'écho intégration et de comptage d'écho. Ce rapport décrit les résultats des études sur trois lacs qui caractérisent la variété de ces applications: Washington, Tustumena et Twin Lakes. Près de 100 études hydroacoustiques y compris des estimations des pré-smolts du saumon sockeye ont été faites sur le lac Washington pendant douze ans. Ces résultats-ci ont été utilisés pour l'aménagement du secteur de la pêche au saumon sockeye et dans l'évaluation des facteurs affectant sa productivité. Les estimations hydroacoustiques ont donné des résultats tout-à-fait comparables aux estimations obtenues par le chalut pélagique. Le lac Tustumena constitue aussi une nourricerie pour ces saumons mais il est plus grand et contient une population répartie de manière plus hétérogène, ainsi qu'une distribution plus proche à la surface. Les estimations effectuées dans ce lac sont le résultat de l'utilisation combinée de transducteurs dirigés vers la surface et vers le fond. Le lac Twin abrite une population de truite lacustre avec des densités très inférieures et une répartition encore plus hétérogène, ce qui a abouti à une plus grande variabilité dans les estimations de population par prospections hydroacoustiques.

1. INTRODUCTION

The Fisheries Research Institute (FRI), University of Washington, has a long history of fisheries work on various lakes. The Institute was established in order to study limnetic factors affecting sockeye salmon (Oncorhychus nerka) production in Alaska. Hydroacoustic twchniques were first used as part of this research in 1961 (Rogers, 1967). The application was limited to echogram counting from commercial echosounders and was not very successful because of the near surface distribution of the fish and limitations of the equipment. In 1968, as part of the newly-organized Sea Grant Program, FRI began research on the echo integration technique, including its application in Lake Washington in 1969 (Thorne and Woodey, 1970). In the subsequent 12 years, FRI has conducted over 200 surveys on 25 different lakes using echo integration and echo counting techniques. This extensive experience has resulted in considerable insight into the advantages and limitations of such applications.

This paper describes studies on three lakes which typify the variety of these applications: Washington, Tustumena, and Twin Lakes. Lake Washington is a sockeye salmon nursery lake near Seattle. Nearly 100 acoustic surveys have been conducted on the Lake including annual estimates of presmolt sockeye salmon populations for 12 years. Lake Washington is well-suited for hydroacoustic techniques. The fish are dispersed in midwater, species composition is relatively simple, and the lake is accessible to large vessels for efficient net sampling.

Three surveys were conducted during 1981 in Lake Tustumena, Alaska, which is also a sockeye salmon nursery lake, but with very contrasting characteristics. The fish are patchily distributed near surface in the large lake (30,000 ha). Access is limited to small vessels.

Twin Lakes in the state of Colorado was surveyed in September 1980, and provides a contrast in both species and distributional characteristics. The primary species is a lake trout (Salvelinus namaycush). These fish are much larger than the juvenile sockeye salmon, but densities were much lower. The lake trout were patchily distributed in deep water, often near bottom. All three lakes have been extensively studied with nets and other traditional techniques for comparison with the hydroacoustic data.

2. GENERAL METHODOLOGY

A variety of equipment and procedures have been used in different lakes and years. In all three lakes the primary mode of data collection was transecting with a down-looking transducer.

For both Lake Tustumena and Twin Lakes, the echosounder was an EK-120 Simrad Scientific Sounder used in conjunction with a 10 degree transducer (full angle, 6 dB down). The pulse length was 0.6 msec. A modified Ross 500 SL chart recorder triggered the echosounder and provided an echogram. The Simrad EK-120 was also used in recent years on Lake Washington, but previously most surveys used a modified Ross 200a echosounder (Thorne et al., 1972), which has a 105 kHz frequency. In all cases the hydroacoustic data are heterodyned to 5-10 kHz and recorded on analog magnetic tape for later analysis.

Data analysis techniques are a combination of echo counting and echo integration. Lake Washington juvenile sockeye salmon surveys were analyzed with echo integration techniqes. The echo integrator used in the initial studies was an analog prototype which is described in Thorne (1971). Subsequent integrators were based on digital computers (Thorne, 1973, 1977) or microprocessors (Wirtz and Acker, 1980). The echo integrator was scaled by means of echo counts and the sample volume was measured by the duration-in-beam technique. This technique is described in many publications including Thorne et al. (1975), Saville (1977), and Nunnallee (1980). In the other surveys, the processing technique was echo counting and sample volume measurement by duration-in-beam. Echo counting was done using a storage oscilloscope. Usually several depths and echo amplitude categories were counted. Further details are given in the specific studies described below.

3. LAKE WASHINGTON

The sockeye salmon in the Lake Washington system spawn primarily in the major tributary, the Cedar River, from October to December. The newly hatched salmon fry enter the lake from the river in February to May and remain for about one year before migrating to the ocean in April and May. The average size at migration is 12-13 cm. The progeny normally return to the lake system to spawn during the summer months after slightly over two years of life in the ocean and die after spawning.

Acoustic surveys have been conducted in the February-March period since 1969 in order to estimate the size of the presmolt population. This information is used as a long range forecast of the size of the returning adult population, as well as a measure of the success of the spawning.

Transecting is done at night to take advantage of the dispersed distribution of fish. Net sampling for species identification is conducted using a 3-m IKMWT (Isaac and Kidd, 1953).

The results of surveys on 13 sockeye salmon year classes are summarized in Table 1 along with information on the size of the parent stock and resulting adult run size. The comparison of 23 acoustic and midwater trawl estimates of presmolt sockeye salmon are shown in Fig. 1. The two estimation techniques compare very well except for two occasions when analysis of the acoustic data demonstrated that the five net sampling areas were not representative of the total lake. Excluding these two points, the correlation coefficient (r^2) is 0.73. The slope of the relationship is 1.04, indicating that the estimates of effective volume filtered by the midwater trawl are very reasonable. A high catching efficiency is expected with the net sampling procedure since the relatively large and effcient IKMWT is towed from a large vessel at 2-5 m/sec at night.

Table 1. Presmolt population estimates and associated run characteristics for 1967 to 1978 brood years.

	Presmolt estimate					
Brood year	Date	Number ($x10^6$)	Parent population ($x10^3$)	Resulting adult run size ($x10^3$)	Marine survival (%)	Return spawners/per
1967	Feb. 69	7.5*	383	559	7.5	1.5
1968	Feb. 70	3.2	252	299	9.4	1.2
1969	March 71	3.8	200	476	12.5	2.4
	April 71	3.6				
1970	March 72	2.0	124	150	7.5	1.2
1971	Feb. 73	1.7	183	144	8.5	0.78
1972	March 74	3.6	249	180	5.0	0.72
1973	Nov. 74	4.1	330	593	-	1.8
	March 75	1.9**				
1974	Feb. 76	0.8**	126	311	-	2.5
1975	March 77	1.1	120	229	20.1	1.9
1976	Feb. 78	4.0	159	500	12.6	3.1
1977	Feb. 79	2.8	275	-	-	-
	March 79	3.1				
1978	March 80	6.6	290	-	-	-
	March 80	7.0				
1979	March 81	3.6	219	-	-	-

*Corrected for drift problems in prototype analog integrator.
**Fish near bottom in south end - known underestimate.

Verification of acoustic results is often difficult to obtain because of the limitations of other techniques for ground truth. The comparison with nets in Lake Washington indicates that the acoustic results are accurate. But in the final analysis, the effectiveness of acoustic techniques depends on how well they provide the necessary information for fishery management purposes. In the case of Lake Washington, this means being able to understand and predict the productivity of the sockeye salmon run. In order to accurately forecast the size of the returning adult run not only do the presmolt estimates need to be accurate, but the marine survival must be known. Marine survival of sockeye salmon is known to be around 10% (Foerster, 1868), but its annual variability is not well-documented. Table 1 shows that estimates of marine survival calculated from the acoustic surveys of presmolts vary from 5.0 to 20.1% and averages 10.4%. The variability may be real or a result of lack of precision in the presmolt estimates. In either case, the utility of the estimates as a forecast are limited by this precision until the sources of uncertainty can be defined and accounted for.

However, another value of the acoustic surveys is to help understand the factors affecting the productivity of the run. Comparison of the average number of presmolts resulting from each spawner with peak water discharge from the Cedar River during the hatching period reveals that flood conditions are the dominant factor affecting spawning success.

4. LAKE TUSTUMENA SURVEYS

Lake Tustumena is a glacial lake in the Kenai National Wildlife Refuge, Kenai Peninsula, Alaska. The lake is 40 km long and 8 km wide. The basin is steep-sloped with a maximum depth about 300 m. The surveys described here are the first results of a five-year program to evaluate the productivity of the lake, and in paticular to evaluate the response of the lake to various stocking levels of sockeye salmon fry.

Hydroacoustic surveys were conducted during three periods of summer 1981: June 2-5; June 28-July 1; and September 21-23. This timing was governed by the release of 8.5 million sockeye salmon fry from the Kasilof Hatchery between the first and second surveys.

Transect locations were determined by dividing the long axis of the lake into eight blocks. One transect was then randomly located within each block and was run twice each survey. Transecting was conducted continuously during periods of low wind velocity. Each fully replicated survey required about 24 hours. In order to minimize boat avoidance by the fish and to survey as close to the surface as possible, the echosounder transducer was towed at the surface in front of the boat from a bow-mounted boom.

In addition to the transecting mode of data collection, data were collected in an uplooking mode in order to examine the near-surface fish distribution. Two types of deployment were used in these measurements, drifting and stationary. In the drifting mode, the EK-120 transducer was suspended from a small surface buoy. A Simrad EY-M scientific echosounder (70 kHz frequency) was used for the stationary deployment. In this case the transducer was lowered to the bottom and the echosounder was located on shore.

Data analysis was done by echo counting, and duration-in-beam measurements as described above.

Each acoustic survey was accompanied by a townet series which consisted of 30 tows at 10 stations. In addition, a limited number of tows were directed by the acoustics for ground truth purposes.

4.1 Vertical Distribution

The vertical distribution of fish as observed during transecting was virtually the same for surveys 1 and 2 with densities highest in the upper interval (2.5-5 m) and decreasing with depth. Fish densities in September were also highest in the upper interval, but were distributed deeper than the earlier surveys.

Diel variability in the vertical distribution of sockeye has been extensively documented. Hydroacoustic surveys in Washington and British Columbia are usually conducted at night to take advantage of more dispersed midwater concentrations. However, the short nights and limited amount of favorable weather conditions precluded stratification of effort on Tustumena Lake by diel period. In order to evaluate this source of variability, the percentage of fish by depth categories was examined by hour of the day. The percentage of fish in the upper 10 m was similar at all times during surveys 1 and 2, which had virtually no dark period. However, diel variability was very obvious during the September survey, which had the longest dark period. A substantial change in the percentage of fish in the upper 10 m in September and comparisons of replicate runs during day and night suggest that the fish are closer to the surface during daylight hours. This unusual diel pattern may be the result of limited light on the feeding behaviour of sockeye in this glacial lake.

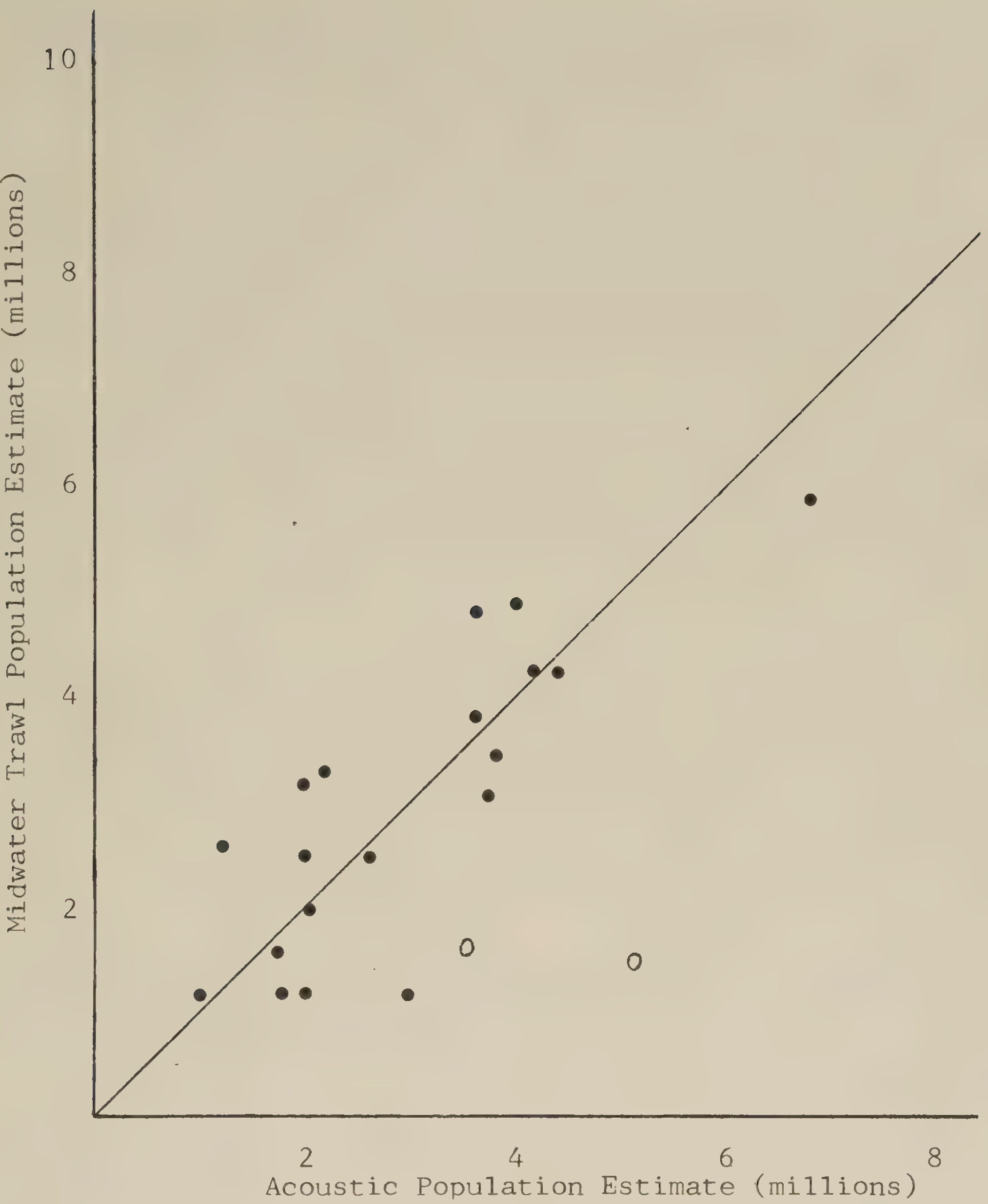

Fig. 1. Comparison of acoustic and midwater trawl estimates of presmolt sockeye salmon, 1970-1981.

The near-surface abundance of fish was examined in greater detail using the up-looking transducers. In this mode it was possible to detect fish targets within 1 ft (0.3 m) of the surface. As suspected from the transect data, fish density in June was higher near surface. However, the density in the upper 5 m was fairly uniform. In contrast, fish densities in the upper 2.5 m, which is not sampled in the down-looking mode, were highest during September. There was also of a diel effect in September, with fish densities even higher in the upper 2.5 m during daylight.

4.2 Population Estimates

Initial population estimates of sockeye salmon and confidence limits (95%) for the three surveys were obtained from the echo counting data by extrapolating the densities in the upper interval (2.5-5 m) to the surface. Potential biases from different densities in the near-surface and multiple targets or other species are considered separately. The estimates were $14.7 \pm 1.97 \times 10^6$, $18.7 \pm 4.82 \times 10^6$, and $5.93 \pm 3.59 \times 10^6$ fish for surveys 1, 2, and 3, respectively. The September survey displayed a larger degree of variation than the June surveys. The coefficient of variation for the September survey was 0.31 compared to 0.07 and 0.13 for the June surveys. The higher variability in September undoubtedly results from the greater diel changes.

The diel effect on the population estimate in September is the result of changes in the proportion of fish in the upper 2.5 m. The correction for bias associated with the assumption of uniform distribution in the upper 5 m would be small for the June surveys. The underestimation in these cases is 0.22×10^6 for survey 1 and 0.30×10^6 for survey 2. However, the underestimation for the September survey is 0.82×10^6 fish.

Unlike Lake Washington, there is little in the way of verification data in Lake Tustumena. The nets that can be towed from the small boats that can access the lake are too inefficient for population estimation. The trend and general magnitude of the three estimates are reasonable. The value of the acoustics in the final analysis will depend on the capability to evaluate the effects of the various stocking levels over the five year program.

5. TWIN LAKES

Twin Lakes, Colorado is the site of the Mt. Elbert Pumped-Storage Powerplant. Concern exists over the effects of the powerplant on the ecology of the lakes, and especially on the lake trout. Previous data on the lake trout have been obtained primarily from experimental gill net studies, sport fishing catches, and limited mark-recapture studies. The limited sampling power, unknown efficiency, and selectivity of gill nets have limited the usefulness of these results, and, in particular, cannot provide adequate estimates of population size. The sport fishing catch data are similarly limited in this regard. The mark-recapture studies also have not successfully provided population estimates because of limited numbers of tags, small number of recaptures, and unknown mortalities.

The acoustic survey was conducted between September 15 and 18, 1980. The survey strategy was to divide the lakes into seven approximately equal parts, five in the lower lake and two in the upper, and to randomly select an orthogonal (north-south) transect location in each of these areas. A total of 19 series, including both day and night transects were run.

Fish densities were sufficiently low for echo counting techniques. The following information was obtained from each target: depth, time along transect, maximum amplitude, and duration-in-beam. The maximum amplitude data were converted to echo strength and categorized in 6-dB intervals. Targets were stratified into three depth zones (3-7.5, 7.5-16, and 16-25 m). The thermocline was at about 10 m.

In addition to the population estimates, various trends in both the numerical and size data were examined. Nonparametric hypothesis testing techniqes were used in order to avoid making assumptions about the underlying distribution of the data (Siegel, 1956).

5.1 Size and Vertical Distribution of Targets

There was a clear vertical separation of two size categories. Most of the echoes from the shallow category were in the smallest detectable echo strength category (-61 to -55 dB) for the gain settings used at Twin Lakes. The mean echo strength from the shallow depth category was -58.4 dB.

The intermediate depth zone had fewer targets and a greater echo strength spread, with a mean echo strength of -50.8 dB. The fish in deep water were considerably larger, with a mean echo strength of -44.5 dB.

Changes in vertical distribution of fish between day and night were detected. The vertical distribution of larger targets (over -49 dB) was broader at night, but still primarily in the deeper water. Very few small targets were observed during the day.

5.2 Population Estimates

Because of the strikingly smaller target strength of the fish above the thermocline, the upper depth strata was treated separately from the deeper two in subsequent analyses. The fact that most of the shallow targets were in the lowest echo strength category indicates that the fish residing at this depth were undersampled.

Three population estimates were made during the survey by combining the data from the two deeper depth strata collected on the upper and lower lake during three periods: nights 1 and 2, night 3, and day 1. The results were 17,389 ± 13,130, 10,206 ± 7,249 and 8,143 ± 8,081; respectively (Table 2). The relative sampling error was highest at 45% for the daytime survey, indicating a more contagious distribution of fish during daylight. The relative sampling error for nights 1 and 2 estimate was higher than night 3 (34% versus 32%) despite complete replication with less than 5% deviation about the mean. This indicated the fish were more contagiously distributed on nights 1 and 2 than on night 3. Despite an approximate twofold difference in the population estimate between nights 1 and 2 and night 3 (night estimates being chosen the best on basis of lower error), the two night-time estimates were within each other's 95% confidence limits. The pooled night surveys produced an estimate of 14,578 ± 10,432.

Table 2. Population estimates of fish in deep and intermediate strata in Twin Lakes.

Survey	Lake	N_T	Var (N_T)	Sampling error	Relative sampling error	95% confidence interval	
						Upper	Lower
Night 2	Upper	961	2.30 E + 05				
Night 1	Lower	16,428	3.42 E + 07				
-	Total	17,389	3.43 E + 07	5,860	34%	34,778	5,259
Night 3	Upper	1,490	1.54 E + 05				
	Lower	8,716	1.07 E + 07				
-	Total	10,206	1.09 E + 07	3,295	32%	17,455	2,957
Day 1	Upper	1,137	3.46 E + 05				
	Lower	7,006	1.31 E + 07				
-	Total	8,143	1.35 E + 07	3,673	45%	16,286	62
Night pooled	Total	14,578	2.54 E + 07	5,040	35%	25,010	4,145

Simultaneous gill net sampling indicated that the species composition below the thermocline was almost exclusively lake trout. Ninety-five percent of the fish from the net samples in this stratum, including 100% in the midwater sets, were lake trout. The intermediate depth stratum in the hydroacoustic estimate extended to 7.5 m, thus it included a few targets from above the thermocline where net samples indicated presence of rainbow and brown trout and suckers, as well as lake trout. However, these gill net sets were on bottom, and other species, especially the suckers, might not have been sufficiently off-bottom for detection with the hydroacoustic system. Thus, it seems reasonable to conclude that the population estimate from the combined deep and intermediate strata is predominantly lake trout.

The only previous population estimate of lake trout in Twin Lakes was obtained from a mark-recapture study. This population estimate of 73,556 with 95% confidence limits of 33,690 to 200,608 was based on only 6 recaptures and some uncertain mortality assumptions (Griest 1977). The hydroacoustic estimate indicates either that the mark-recapture estimate was in error, or that considerable reduction in population occurred between the two estimates.

6. DISCUSSION

Uncertainty in hydroacoustic estimates comes from random and systematic sources. The amount of uncertainty due to random variability can be quantified by the confidence intervals and is genereally a function of the degree of patchiness of the fish distribution and the amount of sampling effort. Under conditions such as Lake Washington where fish are broadly dispersed at night, it is not unusual to obtain confidence intervals better than ±10% of the mean when sampling 1-2% of the water volume. The greater variability in the Lake Tustumena surveys (13% to 61%) reflected greater patchiness, diel variability, and less sampling intensity (0.1%). The 95% confidence intervals for the deeper strata at Twin Lakes were ±72% of the mean, despite a 3-day effort which sampled 5% of the volume, because of the combined low density and contagious distribution. The beam width of the transducer is an important consideration. For example, the relatively narrow beam used at Twin Lakes was completely inadequate for the low densities in the shallow depth strata. Similarly, sampling power under the near surface distribution conditions of Lake Tustumena would have been improved with a wider beam angle. However, the need to resolve primarily single targets also has to be considered in the transducer selection.

Sources of potential systematic error can be categorized into three types: 1) those associated with the techniques for estimating the abundance of hydroacoustically detectable fish targets; 2) error associated with assumptions concerning species composition; and 3) error due to undetected fish targets. Nunnallee (1980) studied the sources and magnitudes of error associated with echo counting techniques including the duration-in-beam method of estimating sampling volume. With reasonable care this source of bias is easily reduced below 10%. A major consideration is to obtain a relatively large mean value for the duration-in-beam by a combination of high pulse repetition rate and slow transect speed. In large deep lakes like Tustumena this may require special measurements.

An additional source of variation is added with the echo integration processing - the relationship between the echo integration and the fish density as determined from the echo counting. For example, in the 1981 Lake Washington survey, the correlation coefficients (r^2) for the regression relationships were 0.75 for the deeper strata where the sockeye salmon were most abundant, and 0.36 for the shallow strata. The greater variability of the latter results from a more diverse size and species mix. This source of variation can be combined with the sampling variation to obtain inclusive confidence intervals as was done by Traynor (1973). His confidence intervals for a single transect series on Lake Washington and this combination of sources of variability ranged from 25% to 55% of the mean estimate for seven different surveys of juvenile sockeye salmon.

Uncertainty associated with species composition can be a major factor depending on the complexity of the lake and the direct sampling capability. In Lake Washington the percentage of the presmolt sockeye salmon has varied from 13% to 90%. However, the ability to deploy a relatively large high speed midwater trawl at night has minimized the species composition problem. In Lake Tustumena, the tow net data indicated that the limnetic fish population was almost exclusively sockeye salmon so that species composition should not be a problem. However, this result may be an artifact of the limited sampling power of the nets which can be towed from small boats. Special net tows directed by the hydroacoustic observations resulted in catches of some species which had not been previously observed in Tustumena. Often the species composition problem can be minimized by taking advantage of the behaviour of the fish. For example, in Twin Lakes the net sampling program had shown that the species of interest - lake trout - was spatially segregated from the other fish during late summer. At other times of the year the mixed assemblage would have greatly confounded the results.

Error due to undetected fish targets can result from inadequate gain or dynamic range or from fish distribution in undetectable areas near boundaries. Analysis of the echo strengths at Twin Lakes clearly demonstrated that the gain settings were inadequate for detection of the small fish component in the shallow water. Similar problems would be encountered in any attempt to enumerate both adult and juvenile sockeye salmon at the same time. The recording of the hydroacoustic signals on analog magnetic tape for analysis in the laboratory further restricts the dynamic range, but is not a major problem since the side lobes of most transducers are only about 30 dB below the acoustic axis (two way) and echo counting techniques should be restricted to the main lobe. The problem can be solved with the appropriate gear selection. For example, the 420 kHz Biosonics 101 echosounder has an 80 dB dynamic range in the receiver and the transducer side lobes are about -70 dB. On the other hand, many applications have used only echogram counts from uncalibrated commercial echosounders, an approach which can lead to major errors.

One of the limitations of hydroacoustic techniques is the inability to resolve targets near bottom and surface boundaries. One of the major problems that was encountered in previous surveys of sockeye salmon nursery lakes in Alaska was the near surface fish distribution (Rogers, 1967; Nunnallee, 1980). The results of the Tustumena study indicate that this problem can be solved by a combination of a transducer towed near surface in front of the boat, careful diel stratification, and supplemental uplooking data. Distribution of fish near bottom has been a problem in some surveys in Lake Washington. Two presmolt surveys, 1973 and 1974 brood year classes, were unsuccessful because the fish were located primarily in the relatively shallow south end of the lake. The problem interacts with the species composition problem. The major difficulty in the Lake Washington surveys was not so much that the fish were unresolvable with the hydroacoustics, but that they could not be sampled with the midwater trawl. Since the sockeye salmon are generally distributed deeper than the other fish species, the species composition data from a shallow net tow is biased when applied to a deeper fish layer. Again, the problems of availability of fish to either acoustic or direct capture gear can often be solved by taking advantage of fish behavior in response to diel or seasonal changes. In one case, a study on Lake Chester Morse near Seattle, hydroacoustic surveys were only successful during the dark stage of the moon (Thorne, 1976).

7. CONCLUSIONS

Over 200 hydroacoustic surveys in 25 different lakes have shown both the problems and potential of the technique. The three lake studies described here represent a sample of the variety. Hydroacoustic techniques obviously are most successful on dispersed, widwater, single species populations. The most difficult conditions are mixed species with near surface or bottom distributions. Most lakes represent conditions in between these extremes, and limitations of the hydroacoustic techniques can be overcome with a well-conceived approach. The hydroacoustic survey design needs to take advantage of available information on the fish behavior and be well-integrated with an appropriate net sampling effort. Sometimes insufficient data are available, and initial surveys are necessary in order to develop the best approach. Many hydroacoustic surveys which have not yielded satisfactory results have been subsequently shown to have been inadequately designed. Long-term studies such as the Lake Washington effort have revealed a variety of problems which need to be taken into account, but have clearly shown the considerable value of hydroacoustics when properly applied.

UNE METHODE DE SIMULATION POUR ETUDIER LA DISTRIBUTION DES DENSITES EN POISSONS: APPLICATION A DEUX CAS REELS

par

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ABSTRACT

A method for the simulation of scattered fish distribution densities is presented. This method consists of defning a distribution diagram for the biomasses (types of heterogeneity, density, shape of the concentrations, etc.) and the corresponding representative density strata, then to calculate the function of distribution per unit of surface for each strata, and finally to generate a density value according to this function and the diagram chosen for each surface unit.

This method has been applied to the results of two surveys which represent extreme situations, i.e. homogeneous, with little contrast of concentration zones (1 to 200 tons/square mile), and heterogeneous, with strong density gradients zones (1 to 200 tons/square mile). These surveys, in Guinea (1978) and Senegal (1976) respectively, have been made by ORSTOM with a SIMRAD echointegration unit.

The results have shown the relation between the variance and the inter-transect distance, this relation depends closely on the type of concentration, the variance evidently being a function of the heterogeneity and level of the measured densities. For example, with a constant inter-transect distance of 20 nautical miles, the confidence interval for the Senegal and Guinea surveys is 80% and 25% respectively.

Finally, various sampling strategies have been tested, consisting principally of a variation in the inter-transect distance with the biomass level. According to the chosen strategy, important reductions of variance have been obtained without using more time in surveying.

RESUME

Une méthode de simulation des distributions de densités en poissons dispersés mesurée par écho-intégration est présentée. La méthode consiste à définir un type de répartition des biomasses et des strates de densités moyennes représentatives, puis à définir des lois de distribution des densités par unité de surface pour chaque strate, efin de générer pour chaque unité de surface une valeur de densité obéissant aux lois et aux canevas choisis.

Cette méthode a été appliquée aux résultats de deux campagnes représentative de deux situations extrèmes: zone à concentrations homogènes et peu contrastées, et zone hétérogège à fort gradient de densité (ORSTOM, Guinée 1978 et Sénégal 1976).

On a pu mettre en évidence les relations entre la variance et l'espacement des radiales; ces relations sont étroitement dépendantes du type de concentration rencontré. Enfin différentes stratégies d'échantillonnage ont été testées. Des diminutions notables de la variance ont pu être obtenues sans avoir à augmenter sensiblement le temps de campagne.

1. POSITION DU PROBLEME

L'écho-intégration dans son application présente fondamentalement deux types d'erreurs.

Les uns, internes, sont ceux de la méthodologie, de l'appareillage et de la calibration. Ce sont probablement les plus importants, bien qu'il soient souvent omis, et pour cause: il s'aigit la plupart du temps d'erreurs systématiques. Citons par exemple les risques de saturation, à divers niveaux, les erreurs dues à la meconnaissance du comportement du poisson, de l'écosystème, etc. Or ces risques sont importants car une fois les données recueillies, il n'y a souvent aucun moyen de déterminer si elles sont ou non entachées d'erreurs.

Celà dit il n'est guère d'exemples dans la littérature de résultats manifestement aberrants. Après dix ans d'usage, l'expérience montre que l'écho-intégration est au moins un bon indicateur pour ce qui concerne les ordres de grandeur des biomasses halieutiques et un excellent outil pour en photographier la répartition.

Le second point important à étudier est celui de l'échantillonnage. On se trouve ici devant un problème plus classique, sans pour celà qu'il en soit d'ailleurs plus facile à résoudre.

Si l'on considère en effet comme résolus tous les points rappelés auparavant, reste celui de la collecte des données, qu l'on peur résumer ainsi:

1) Quelle est la précision des résultats d'une campagne hydroacoustique?

2) Quel est le plan de campagne "idéal", donnant à la fois la meilleure précision et la durée (ou distance) de prospection la plus courte?

C'est à ces deux points que le présent travail tâche d'apporter quelques lumières. Nous avons dû pour celà négliger un certain nombre de paramètres importants, dont le plus considérable est le caractère fluctuant et non statique du terrain d'observation, tout en sachant que cette hypothèse limite nécessairement la portée de nos calculs.

2. ESTIMATION DE L'INCERTITUDE DUE A L'ECHANTILLONNAGE

On se trouve icei devant un problème classique de définition de la dimension minimale d'un échantillon pour une précision déterminée. Le calcul consiste à comparer un échantillon dont on fait varier la taille à la population dont il est issu, et à déterminer par des tests adéquat la taille la plus petite à partir de laquelle les différence existant entre l'échantillon et la population peuvent être considérées comme non significatives au seuil que l'on s'est fixé.

Le point le plus délicat dans ce type de calcul réside en général dans la difficulté où l'on se trouve souvent de connaître la population réelle, soutout losqu'il s'agit d'une population qui n'est pas distribuée selon une loi normale. Dans notre cas particulier c'est impossible. En revanche, dans la mesure où cette population peut être définie par quelques lois simples, ou qu'elle peut être représentée par les quelques hypothèse qui seules nous intéressent, il devient possible de créer une population fictive par simulation et d'y établir un système d'échantillonnage plus ou moins serré que l'ont peut ensuite tester. Cette méthode fut employée par Fiedler (1978) sur les bancs d'anchois du Pacifique (Engraulis mordax). Dans notre cas il ne s'agit pas de bancs mais de poissons dispersés, aussi si le principe est à peu près semblable, la méthode de simulation est-elle distincte.

Nous avons défini la population comme un ensemble de surfaces unitaires carrées ayant comme côté la longueur d'une unité élémentaire d'échantillonnage, ou ESDU (Elementary Sampling Distance Unit), de densité en poissons supposée homogène.

Nous décrivons cette population par trois lois:

- loi de stratification des densités: les carrés élémentaires ne sont pas répartis de façon aléatoire dans la région etudiée, et se rassemblent par groupes de densité voisine pour former des ensembles relativement homogènes que l'on considérara comme des strates. Celles-ci sont établies à l'oeil pour chaque campagne afin de représenter au mieux les

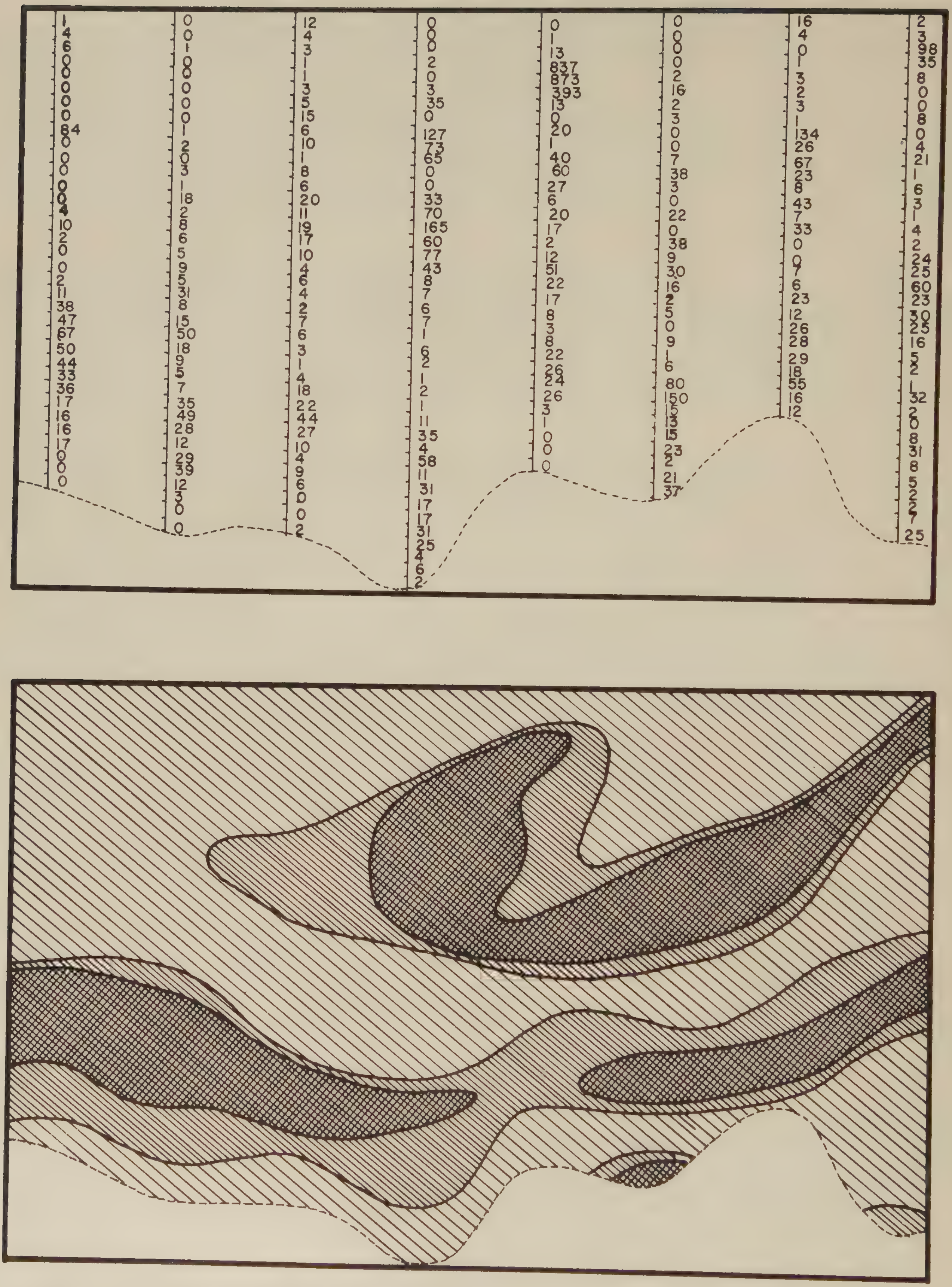

Fig. 1: Radiales GUINEE 2 (valeurs observees en tonnes par mille carre) et stratification correspondante.

▨ 0-10 tonnes / mille ^{2} ▨ 10-30 t. / mille ^{2} ▩ 30 t. / mille ^{2}

les zones de concentrations. Dans la plupart des cas l'expérience a montré que la meilleure échelle de stratification est approximativement logarithmique et comprend de trois à cinq strates, par exemple 0/5, 5/50, 50/500 et supérieure à 500 tonnes par mille carré.

- loi de distribution géographique: la répartition des biomasse de poissons, en tous cas dans les eaux africaines, obéit à certains schémas globaux, et plusieurs cas peuvent se présenter:

  a) biomasse répartie en petites concentrations éparpillées sur l'ensemble de la zone;

  b) biomasse rassemblée en une concentration principale sur un petit secteur de la zone;

  c) biomasse étirée en une concentration le long d'une sonde d'un bout à l'autre de la zone.

- loi d'autocorrélation: il faut enfin définir s'il existe ou non une corrélation significative entre deux densités voisines et, si cette "autocorrélation" existe, déterminer à quelles lois elle obéit.

2.1 Principe

2.1.1 Choix des distributions géographiques

La simulation s'est alors déroulée en deux étapes. Tout d'abord nous avons déterminé chacun des paramètres énumérés ci-dessus à l'aide des campagnes effectuées dans la région, puis les hypothèse faites, nous avons crée des populations sur lesquelles les tests d'échantillonnage ont été calculés.

Nous avons utilisé dans cette étude les données de base de deux campagnes hydro-acoustiques qui présentent l'intérêt d'être parmi les plus dissemblables, si on les compare au niveau des trois lois fixées.

La campagne CAP 7605 (Gerlotto et al., =976) présente une population très hétérogène, aussi bien au niveau de la répartition géographique, de type (b), qu'à celui des distributions en fréquence des densités (de 0 à plus de 1 000 tonnes par mille carré).

La campagne GUINEE 2 (Marchal et al., 1979) est beaucoup plus homogène, les répartitions des concentrations étant de type (c) et le spectre des densités beaucoup plus réduit (de 0 à 200 tonnes par mille carré). Pour accentuer cette différence netre les deux campagnes, nous n'avons pris en considération que la partie la plus homogène de GUINEE 2 (Fig. 1).

2.1.2 Détermination des lois de distribution des densités

Il est bien évident que les densités en poissons ne sont pas réparties de façon purement aléatoire. Nous avons donc considéré les phénomènes de concentration à deux niveaux. Au niveau de la région représentée dans son ensemble, le phénomène de contagion est pris en compte par la stratification générale de la zone, qui distinque zones riches et zones vides. Le deuxième niveau est celui de la corrélation existant entre les densités de deux ESDU consécutifs. Au niveau de notre simulation nous avons décidé tout d'abord de négliger cette autocorrélation afin de pouvoir générer plus facilement des valeurs d'ESDU, quitte par la suite à vérifier le bien fondé de notre hypothèse.

La détermination des lois de distribution se fait de la manière suivante: les polygônes de fréquence des densités par deux milles ont été dressés pour chaque strate à partir des données de la campagne CAP 7605 et GUINEE 2 (Figs. 2 et 3). Nous avons ensuite tenté d'extraire pour nos populations simulées des lois de distribution de densité empiriques correspondant aux diagrammes obtenus à partir des valeurs observées, après lissage. Cette opération a été effectuées pour chacune des strates. Les lois de distribution sont difficiles à établir et n'apporteraient pas de renseignements supplémentaires, aussi nous sommes-nous contentés de calculer à partir des courbes lissées obtenues les probabilités pour chaque classe. A partir de ces distributions observées, nous avons crée des radiales aux emplacement des radiales de la campagne, en tirant au hasard des valeurs suivant les lois de probabilitié de chaque strate.

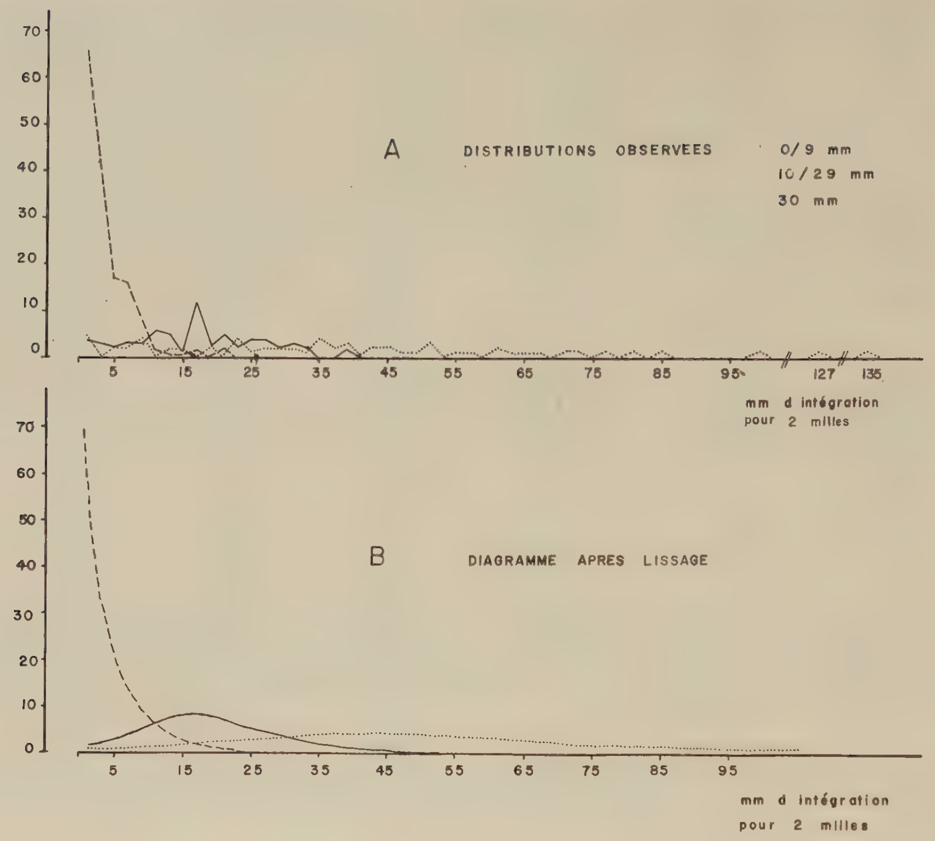

Fig. 2: Polygône observé et diagramme de fréquence des distributions de densité dans chaque strate (GUINEE 2).

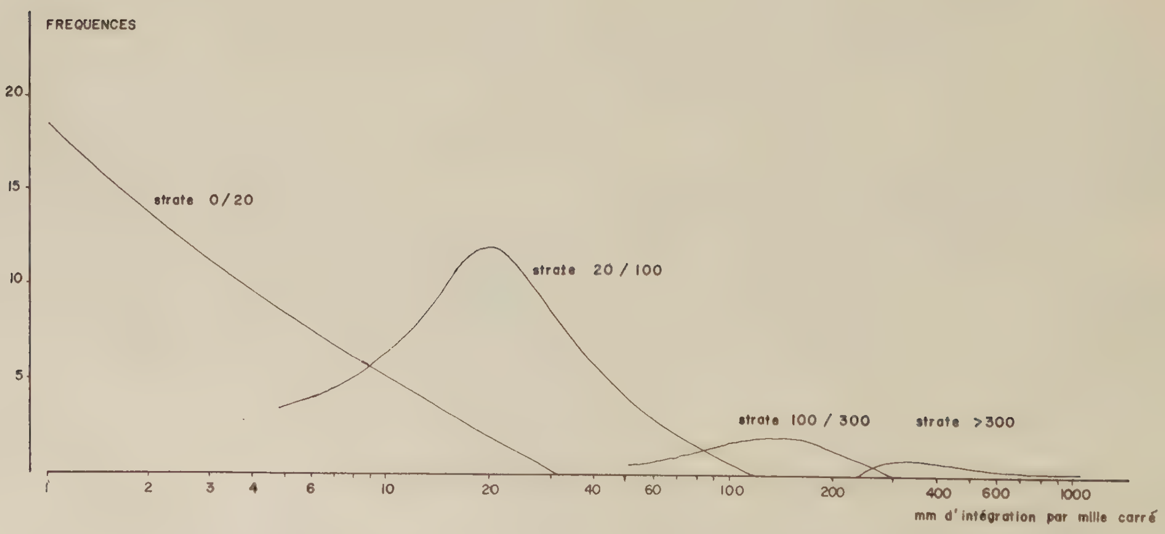

Fig. 3: Diagramme de fréquence des densités dans chaque strate (CAP 7604).

Il faut alors vérifier si les distributions simulées représentent de façon satisfaisante les distributions réelles à l'intérieur des strates.

Dans un premier temps nous avons simplement comparé les courbes de densité observées sur les radiales aux courbes simulées (Fig. 4). La simple comparaison à l' oeil permet déjà de mettre en évidence qu'au niveau grossier qui nous intéresse la similitude entre les deux courbes est très satisfaisante. Nous considérerons donc que pour une étude des variations entre les radiales, une simulation peut être faite en tirant au hasard les valeurs suivant les lois de probabilité mises en évidence.

Cette comparaison appelle cependant d'autres observations. Il semble intéressant de vérifier si les ESDU présentent vraiment cette indépendance que l'on a admise pour les valeurs simulées.

Pour celà nous avons fait une comparaison suivant le principe décrit ci-dessous: pour chaque radiale on calcule les moyennes mobiles sur cinq valeurs à partir des données observées. Ces moyennes représentent l'évolution générale de la densité le long d'une radiale, nous les considérerons comme un indice des tendances de la densité. On calcule ensuite la variance des valeurs observées en prenant pour moyenne la valeur lissée correspondante pour chaque donnée. En toute logique, et si la stratification ne suffit pas à représenter l'interdépendance des ESDU, autrement dit s'il existe une autocorrélation, la variance des valeurs observées doit être bien inférieure à celle des valeurs simulées. En effet celles-ci, dans le cadre d'une strate, n'ont par construction aucune autocorrélation.

Le cas de la campagne GUINEE 2 montre clairement que les variances des deux séries sont assez proches (environ 18%, soit un rapport entre variance observée et simulée de 1,21) (tabl. 1).

Il est difficile de tester l'égalité des variances ainsi calculées. De plus on peut penser que la valeur de la variance des densités observées est influencée par les quelques très fortes valeurs rencontrées (par exemple l'ESDU de 84 dans la radiale 1). On pourrait en fait concevoir que les valeur observées, hors ces quelques exceptions, suivent étroitement les valeurs lissées, avec donc une faible variance. Il pourrait alors y avoir une forte autocorrélation des ESDU en général, masquée par des exceptions (bancs, par exemple).

Pour vérifier ceci nous avons calculé pour chaque radiale, puis pour l'ensemble des valeurs, le coefficient de corrélation de rang de Spearman entre valeurs observées et lissées correspondantes, puis entre valeurs simulées et lissées.

Les résultats, présentés dans le tableau 2, montrent bien que les distributions simulées et observées sont très proches. Nous avons testé l'égalité des deux coefficients (Dagnelie, 1975), et constaté que dans aucun cas l'hypothèse d'égalité n'a pu être rejetée au seuil de 5%.

On se permettra donc, dans le cadre de nos hypothèse, de déclarer que la stratification retenue peut être suffisante pour décrire les agrégations de la biomasse et que, à l'intérieur d'une strate, les variations de densité entre les ESDU sont imputables à un "bruit de fond".

Nous n'avons pas poussé plus loin l'étude de ce phénomène, mais il correspond à une observations courante dans les campagnes d'écho-intégration: il est par exemple illusoire de vouloir retrouver les mêmes valeurs de densité en repassant deux fois au même endroit. La répartition ponctuelle des concentrations évolue avec une grande rapidité. Ce phénomène est particulièrement net dans le cas des petits pélagiques comme les Clupéidés, les Engraulidés, etc.

Le caractère apparemment aléatoire des densités à l'intérieur d'une strate est le seul qui dans notre étude rende compte quelque peu des fluctuations temporelles des biomasses halieutiques. Quoi qu'il en soit, cette approximation simplifie de beaucoup les problèmes de simulation, laquelle revient alors à effectuer deux opérations:

RADIALE 1			RADIALE 2			RADIALE 3			RADIALE 4			RADIALE 5			RADIALE 6			RADIALE 7			RADIALE 8		
vo	vs	vm	vo	vs	vm	vo	vs	vm	vo	vs	vm	vo	vs	vm	vo	vs	vm	vo	vs	vm	vo	vs	vm
1	0		0	7		12	0		0	10		0	7		2	1		16	0		2	2	
4	5		0	4		4	4		0	8		0	1		0	5		4	4		3	8	
6	1	2.2	1	1	0.2	3	4	4.2	0	0	0.4	13	16	344.8	0	0	0.8	0	9	4.8	98	196	29.2
0	20	2.0	0	4	0.2	1	2	2.4	2	0	1.0	837	57	423.4	0	3	3.6	1	16	2.0	35	44	28.8
0	0	1.2	0	1	0.2	1	1	2.6	0	3	8.0	873	48	425.8	2	0	4.0	3	12	1.8	8	4	28.2
0	5	0.0	0	0	0.0	3	3	5.0	3	1	8.0	393	55	423.2	16	4	4.6	2	8	2.0	0	2	10.2
0	0	16.8	0	8	0.2	5	2	5.2	35	10	33.0	13	26	259.8	2	93	4.2	3	32	28.0	0	3	3.2
0	0	16.8	0	2	0.6	15	1	7.0	0	53	47.0	0	14	85.4	3	0	2.4	1	9	33.2	8	0	2.4
84	2	16.8	1	14	0.6	2	4	6.6	127	23	59.8	20	15	14.8	0	0	9.6	134	30	44.2	0	0	6.6
0	4	16.8	2	16	1.2	10	17	7.2	72	24	52.8	1	0	24.2	0	0	9.6	26	140	48.2	4	5	6.8
0	0	16.8	0	7	1.4	1	6	5.4	65	22	52.8	40	47	29.6	7	5	9.6	57	36	49.0	21	7	6.4
0	12	0.0	3	0	3.4	8	15	9.0	0	29	34.0	60	40	26.8	38	34	14.0	23	23	30.8	1	1	7.0
0	3	0.8	1	9	3.4	6	16	9.2	0	26	33.6	27	39	30.6	3	47	12.6	5	80	27.0	6	3	6.4
0	2	2.8	11	1	4.2	20	5	12.8	33	36	53.6	6	26	26.0	0	6	13.8	43	6	22.2	3	0	3.0
4	3	3.2	2	4	4.0	11	14	14.6	70	33	65.6	20	29	14.4	22	40	19.8	7	61	17.6	1	1	3.2
10	1	5.4	4	4	5.6	19	26	15.4	165	34	81.0	17	15	11.4	0	166	18.6	33	10	16.6	4	12	6.8
2	1	13.0	6	1	5.2	17	32	12.2	60	197	83.0	2	15	20.4	38	222	19.0	0	0	9.4	2	2	11.2
11	16	21.6	5	12	5.8	10	11	11.2	77	51	70.6	12	173	20.8	9	30	12.4	0	0	9.2	24	19	23.0
38	1	33.0	9	2	11.2	4	5	8.2	43	22	39.0	51	18	20.8	30	30	10.6	7	8	7.2	25	2	26.8
47	58	42.6	5	15	11.6	6	9	5.2	8	30	5.8	22	60	22.0	16	21	6.4	6	4	9.6	60	56	32.4
67	46	49.2	31	37	13.6	4	2	4.6	7	0	14.2	17	36	20.2	2	10	3.4	23	35	14.8	23	21	32.6
50	57	48.2	8	42	21.0	2	6	5.0	6	5	5.8	8	0	11.6	5	21	4.2	12	45	19.0	30	37	30.8
44	24	46.0	15	65	24.4	7	2	4.4	7	5	5.4	3	1	11.6	0	10	19.2	26	30	23.6	25	63	19.8
33	43	36.0	50	12	20.0	6	2	3.8	1	7	4.4	8	8	13.4	9	3	49.2	28	9	22.6	16	26	15.6
36	4	29.2	18	44	19.0	3	3	4.2	6	1	3.4	22	28	16.6	1	17	50.4	29	5	31.2	5	4	9.8
17	12	23.6	9	31	17.4	1	0	6.4	2	1	2.4	26	6	21.2	6	28	52.8	18	55	29.2	2	20	11.2
16	40	17.0	3	56	14.4	4	1	9.6	1	1	2.4	24	20	20.8	80	78	54.6	55	31	26.0	1	41	8.4
16	14	9.8	7	67	20.6	18	19	17.8	2	0	3.4	26	2	16.4	150	2	41.2	16	30		32	22	7.4
0	14	6.4	35	43	24.4	22	27	23.0	1	7	10.0	6	0	11.2	15	8	14.2	12	18		2	3	8.6
0	2		49	35	26.2	44	104	24.2	11	7	10.6	0	8	6.4	13	8	17.8				0	2	14.6
0	3		28	35	30.6	27	13	21.4	35	27	21.8	0	9		15	30	15.6				8	5	9.8
			12	28	31.4	10	15	18.8	4	18	23.8	0	0		23	33	16.8				31	3	10.4
			29	32	24.0	4	15	10.2	58	30	27.8				2	2	21.6				8	10	10.8
			39	28	19.0	9	13	4.8	11	21	24.2				21	1					5	3	9.6
			12	20	16.6	1	6	2.8	31	20	26.8				37	50					2	1	4.8
			3	7	10.8	0	10	2.4	17	11	21.4										2	2	8.2
			0	5		0	2		17	16	21.2										7	12	
			0	20		2	13		31	17	18.8										25	25	
									25	16	12.8												
									4	3	15.8												
									2	4													
									2	2													
Vo=304.6 Vs=199.3 n = 27			Vo=105.0 Vs=264.7 n = 34			Vo= 27.4 Vs=230.0 n = 34			Vo=6333 Vs=4993 n = 38			Vo=20525 Vs=22703 n = 28			Vo= 739 Vs=2714 n = 31			Vo=542 Vs=736 n = 25			Vo= 246 Vs=1031 n = 34		

Tableau 1: Mesure de variance pour chaque radiale (campagne GUINEE 2)
vo: valeur observee; vs: val. simulee; vm: val. moyenne lissee
Vo: variance des vo; Vs: variance des vs

RADIALE	n	r(vo,Vm)	r(Vs,Vm)	u (*)
1	27	0.777	0.457	1.109
2	34	0.879	0.511	1.449
3	34	0.793	0.650	0.563
4	38	0.673	0.856	0.766
5	28	0.471	0.582	0.393
6	31	0.357	0.357	0.000
7	25	0.603	0.4555	0.491
8	34	0.550	0.621	0.281

Tableau 2: Valeur du coefficient de correlation de rang de Spearman pour les radiales de GUINEE 2
Vo: valeurs observées; Vs: val. simulées; Vm: val. lissées
(*) u * test d'égalité des coefficients

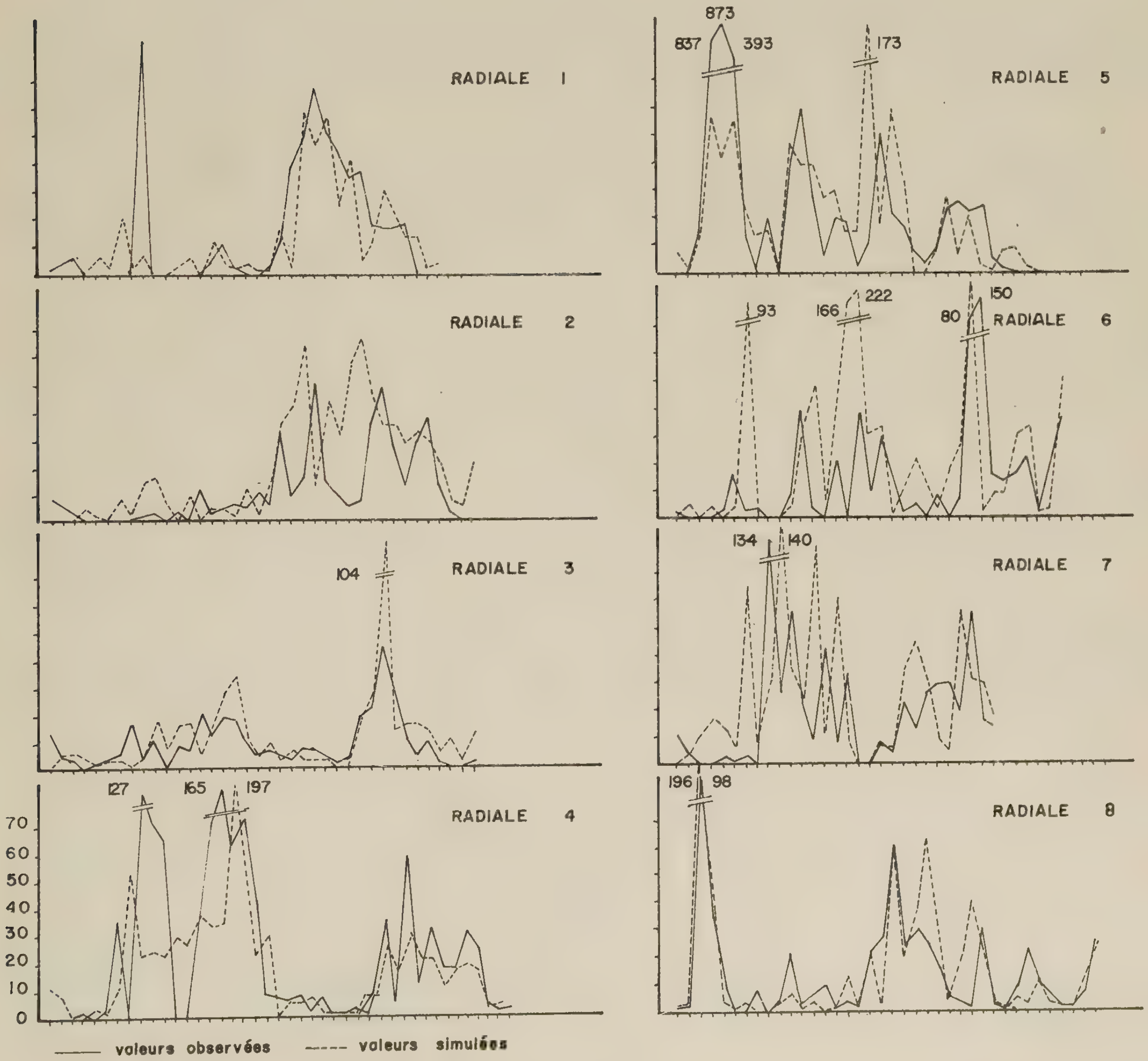

Fig. 4: Relation entre valeurs observées et calculées pour chaque radiale (GUINEE 2).

Nombre de radiales	distance entre 2 radiales (milles)	Biomasse (en tonnes)	écart type	Coefficient de variation (en %)	Intervalle de confiance (en %) *	Ecart par rapport à la valeur calculée totale
40	4	219 700	7 500	3,4	6,8	4,4 %
40	4	215 000	10 500	4,9	9,8	2,3 %
16	10	255 800	14 323	5,6	11,2	17,9 %
16	10	241 000	26 200	10,9	21,8	12,9 %
16	10	192 600	10 200	5,3	10,6	9,0 %
16	10	190 300	10 800	5,7	11,4	10,4 %
16	10	221 300	8 685	3,9	7,8	5,1 %
8	20	230 000	24 300	11,0	22,0	8,7 %
8	20	253 000	45 000	18,0	36,0	17,0 %
8	20	204 600	29 100	14,2	28,5	2,6 %
8	20	262 800	28 200	10,7	21,5	20,1 %
8	20	190 700	13 300	7,0	14,0	10,1 %
6	30	302 000	53 100	17,6	35,2	30,5 %
6	30	214 000	25 400	12,0	24,0	1,9 %
6	30	226 600	6 753	3,0	6,0	7,3 %
6	30	241 900	22 300	9,2	18,4	13,2 %
6	30	217 400	14 400	6,6	13,2	3,4 %
4	40	301 000	94 700	31,5	63,0	30,2 %
4	40	204 000	8 880	4,5	9,0	2,9 %
4	40	196 000	3 250	1,5	3,0	7,1 %
4	40	204 200	38 400	18,8	37,6	2,8 %
4	40	207 500	12 400	5,9	11,8	1,2 %
4	50	313 300	103 400	33,0	66,0	33,0 %
4	50	196 500	22 300	11,4	22,8	6,9 %
4	50	217 400	15 500	7,1	14,2	3,4 %
4	50	228 500	44 200	19,4	38,7	8,1 %
4	50	256 000	75 600	29,5	59,0	18,0 %

Tableau 3: Etude de la variance sur l'estimation de la biomass de la campagne GUINEE 2. * au seuil de 5%
(La biomasse simulée totale est de 210 000 tonnes)

Nombre de radiales	distance entre 2 radiales (en milles)	Biomasse (en tonnes)	Ecart type	Coefficient de variation (en %)	Intervalle de confiance (en %)	Ecart par rapport à la valeur calculée totale
36	4	751 100	68 600	9,1	18,2	2,8 %
36	4	798 800	50 800	6,4	12,7	3,1 %
14	10	875 300	247 000	28,2	56,4	11,7 %
14	10	705 100	57 800	8,2	16,4	8,8 %
14	10	709 600	93 800	13,2	26,4	8,2 %
14	10	827 700	229 400	27,7	55,4	6,6 %
14	10	699 400	97 700	14,0	28,0	9,5 %
12	12	718 200	120 100	16,7	33,4	7,1 %
12	12	627 200	232 300	37,0	74,0	18,9 %
12	12	784 300	240 700	30,7	61,4	1,4 %
12	12	793 700	274 500	34,6	69,2	2,6 %
10	16	914 200	372 200	40,7	81,4	15,4 %
8	16	726 200	181 500	25,0	50,0	(*)
8	20	833 700	332 700	39,9	79,8	7,3 %
8	20	817 500	323 900	39,6	79,2	5,4 %
8	20	824 300	323 600	39,3	78,6	6,2 %
8	20	675 200	323 200	47,9	95,8	12,7 %
6	26	866 500	457 300	52,8	105,6	10,8 %
6	26	1 093 000	728 000	66,6	133,2	29,3 %
6	26	825 600	507 600	61,5	123,0	6,4 %
6	26	763 400	432 400	56,6	113,2	1,2 %
6	28	902 400	513 400	56,9	113,8	14,3 %
6	28	634 400	294 500	46,2	92,4	17,9 %
4	44	643 000	258 000	40,1	80,2	16,8 %
4	48	551 300	270 800	49,1	98,2	28,7 %

Tableau 4: Etude de la variation sur l'estimation de campagne CAP 7605.

- tracer pour chaque campagne ou chaque type de campagne les enveloppes correspondant aux strates;

- à partir des lois de probabilité des distributions des densités dans chaque strate, affecter chaque surface unitaire d'une densité tirée au hasard.

Dans ces conditions il devient possible de simuler des distributions purement fictives. Nous nous sommes contentés dans cette étude de poursuivre la simulation à partir de campagnes réelles, afin de cerner au plus près la réalité. Nous avons donc simulé les campagnes GUINEE 2 et CAP 7605, en conservant les cartes, les strates et les distributions observées.

2.2 Résultats

Nous présentons sur la figure 5, à titre d'exemple, la carte obtenue par simulation de CAP 7605, sur laquelle diverses stratégies d'échantillonnage ont été testées. Les échantillonnages par radiales ont été effectués pour les deux campagnes.

2.2.1 Calcul de la variance

Nous avons appliqué la méthode de calcul de la variance mise au point par Bazigos (1975). Elle est particulièrement bien adaptée à notre sujet puisque nous ne nous intéressons qu'aux valeurs globales des radiales, ayant vu que la variance intra-radiale est dans notre cas irréductible.

Par cette méthode nous calculons variance, écart-type, coefficient de variation et intervalle de confiance (à 5%), en diminuant progressivement le nombre de radiales dans notre échantillon. Rappelons ici que nous considérons pour le moment toutes les autres sources d'erreur comme négligeables (ce qu'elles ne sont pas) pour simplifier notre étude.

2.2.2 Campagne GUINEE 2

Cette campagne présente une biomasse répartie de façon assez homogène, taut au niveau des densités (0 à 200 tonnes par mille carré) qu'au niveau de la position géographique des zones denses, qui s'étendent sur une bande parallèle à la côte d'un bout à l'autre de la région prospectée. La biomasse totale simulée est de 228 000 tonnes.

Nous avons échantillonné cette zone par des radiales parallèles, espacées successivement de 4, 10, 20, 30, 40 et 50 milles. Les résultats sont regroupés dans le tableau 3 et représentés sur les figures 6 et 7. On voit que l'intervalle est proportionnel à l'écartement inter-radiales et qu'il augmente de manière approximativement linéaire jusqu'à l'espacement maximum simulé.

Ce type de répartition de la biomasse ne semble donc pas nécessiter un échantillonage très serré, puisque si l'on se contente d'un intervalle de confiance de 25% de la biomasse, soit une fourchette de 168 à 282 000 tonnes, l'espacement inter-radiales peut aller jusqu'à 25 milles.

2.2.3 Campagne CAP 7605

Dans cette campagne, les densités varient 5 fois plus que lors de la campagne GUINEE 2 (0 à plus de 1 000 tonnes) et la biomasse est surtout concentrée dans le sud de la zone étudiée.

Il a donc été nécessaire d'augmenter le nombre de strates à 4 pour avoir une bonne représentation graphique des concentrations. Nous avons ensuite procédé de la même manière que pour l'exemple précédent (Fig. 6). Dans ces conditions, l'évolution de la variance est beaucoup plus marquée que lors de la campagne GUINEE 2, et il devient nécessaire d'effectuer une radiale tous les 6 milles.

On peut également noter que passé l'écartement de 30 milles, l'intervalle de confiance diminue notablement. Ceci est dû au fait qu'il ne nous a pas été possible d'effectuer des échantillonnages répartis sur l'ensemble de l'aire observée, et que les radiales ne sont pas passées dans les zones de forte concentration, comme l'indiquent d'ailleurs les faibles valeurs de biomasse calculées (tabl. 4).

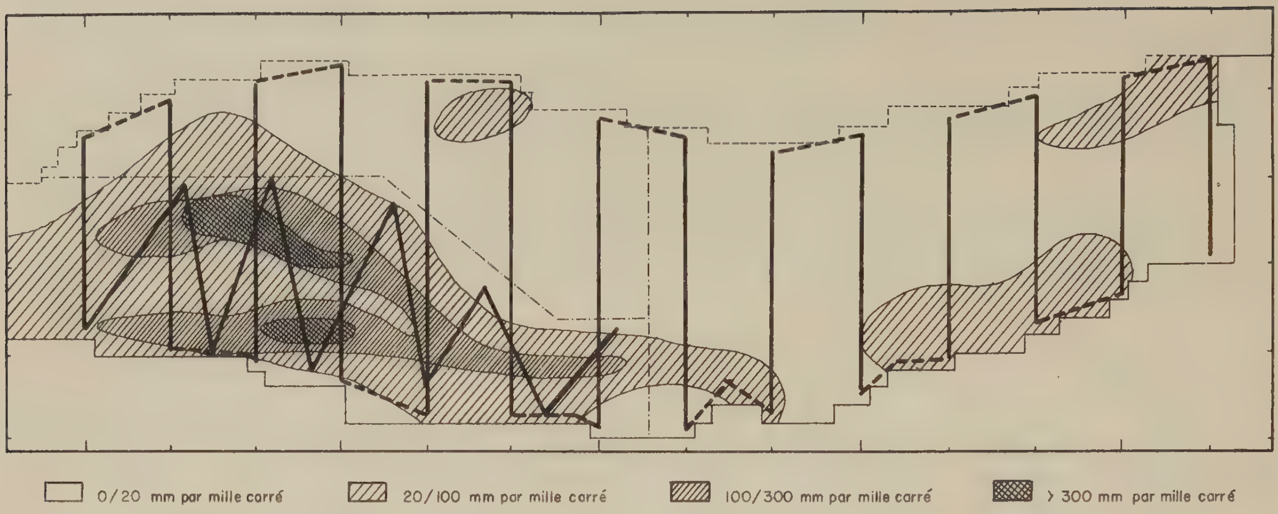

Fig. 5: Campagne CAP 7605. Exemple de stratégie d'échantillonnage.

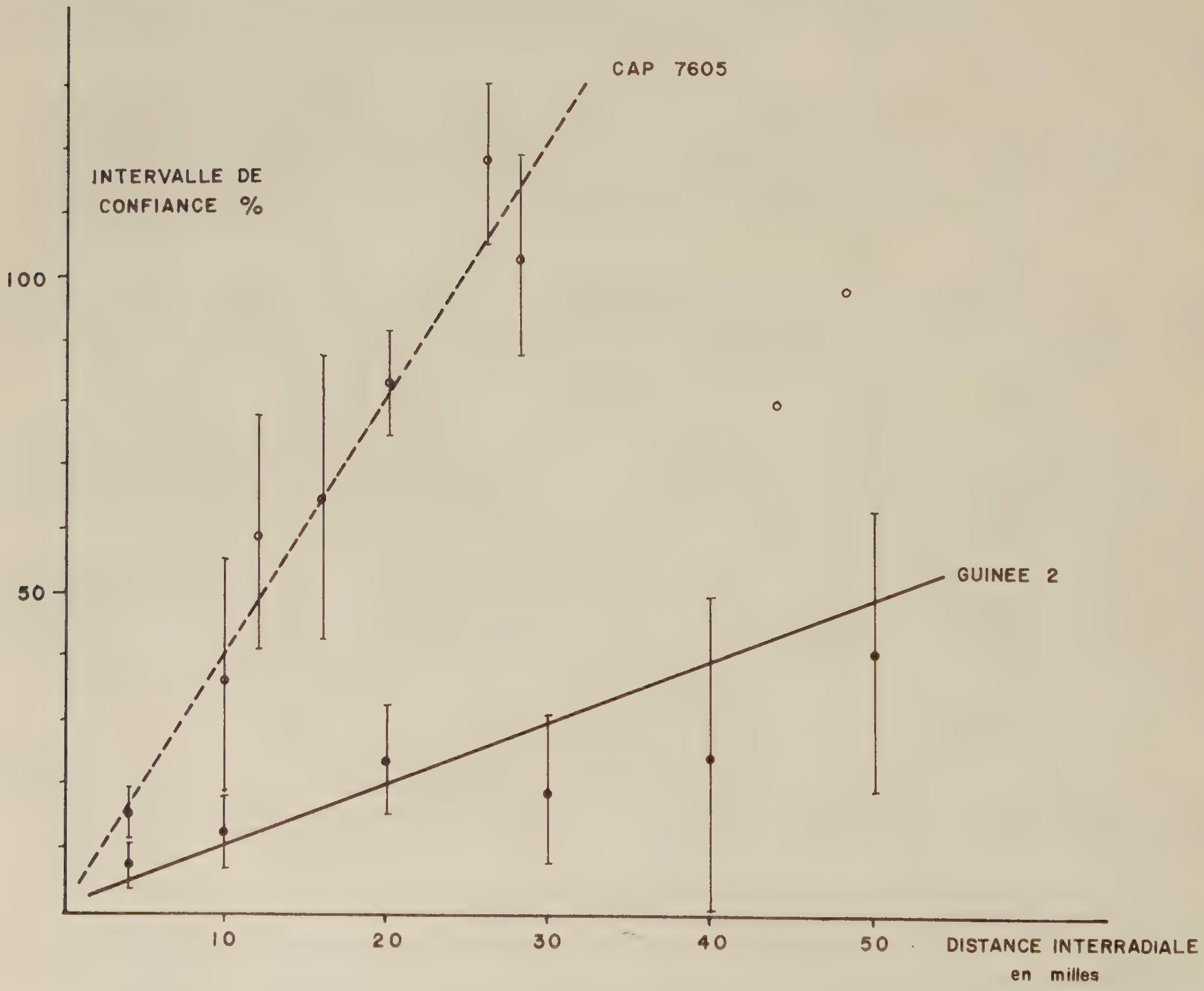

Fig. 6: Evolution de l'intervalle de confiance en fonction de l'écartement des radiales.

Ce phénomène permet de constater qu'il arrive un moment où l'espacement des radiales est tel que non seulement la biomasse, mais même la variance, ne signifient plus rien. Les courbes que nous présentons (Fig. 6) ne peuvent donc certainement pas être extrapolées. Rappelons en effet que la méthode de calcul de la variance utilisée suppose que les sous-régions soient homogènes, et qu'à partir d'un écartement limité cette hypothèse n'est plus vraie et la méthode devient impraticable.

2.2.4 Application aux campagnes réelles

- Campagne GUINEE 2: nous n'avons pris dans notre essai de simulation que le secteur le plus large et le plus régulier du plateau continental. Dans ce secteur, avec des radiales espacées de 18 milles et une constante d'intégration de 1, la biomasse estimée était de 226 000 tonnes. Se référant à la courbe de l'intervalle de confiance, à 18 milles d'espacement inter-radiales correspond un interva-le de confiance de 19%, soit 43 000 tonnes, et la biomasse doit être comprise entre 184 000 et 270 000 tonnes.

- Campagne CAP 7605: nous avons utilisé pour notre simulation l'ensemble du plateau continental de Dakar au Cap Roxo. Pour une constante de 4.5 et un espacement des radiales de 10 milles, la biomasse estimée était de 780 000 tonnes. L'intervalle de confiance pour un écartement de 10 milles est de 40%, et la biomasse réelle est donc comprise entre 468 000 et 1 092 000 tonnes.

3. DISCUSSION

La comparaison des évolutions du coefficient de variation dans les deux campagnes montre que celui-ci est essentiellement affecté par la répartition de la biomasse au sein de l'aire étudiée. La plus simple méthode pour réduire la variance, en particulier dans le cas de CAP 7605, est probablement de changer la stratégie d'échantillonnage, et de stratifier la région étudiée en zones riches et pauvres.

Dans cette optique, nous avons effectué, dans un premier temps, une campagne simulée en séparant la zone en deux secteurs: secteur pauvre (radiales 1 à 36) et secteur riche (radiales 37 à 72). En réalisant une radiale tous les 20 milles dans la zone pauvre et tous les 4 milles dans la zone riche, nous obtenons un coefficient de variation identique à celui obtenu en utilisant pour l'ensemble de la campagne un espacement de 4 milles. Il est donc intéressant de noter qu'en utilisant une stratégie différente nous avons pu faire l'économie de 16 radiales sans augmenter sensiblement la variance.

Cependant ce type de modulation de parcours n'est pas tout-à-fait satisfaisant, ceci pour trois raisons.

Tout d'abord il rallonge passablement le temps de parcours, par rapport à la campagne initiale à radiales tous les 10 milles, de plus de 60 milles dans le cas que nous venons de voir, ceci sans apporter beaucoup de bénéfices dans 1/3 de la surface, au large, dans les eaux peu peuplées.

Ensuite il ne répond pas au mieux aux observations que nous avons faites, àsavoir:

- que les densités individuelles ne sont pas statiques ni autocorrélées, ce qui revient à dire que dans chaque strate et passé un certain niveau d'échantillonnage, resserrer les radiales ne fait guère gagner de précision sur les résultats; nous avons calculé qu'avec une cinquantaine d'ESDU par strate la densité moyenne est connue avec une précision suffisante.

- que ce sont les strates et leur extension qui gouvernent la biomasse.

Enfin, dans la pratique, le navire prospecteur est souvent aussi celui qui échantillonne par pêche. Il est donc amené à circuler plus longtemps dans les zones riches à la recherche de détections capturables, donc pas toujours en suivant une route rigidement imposée.

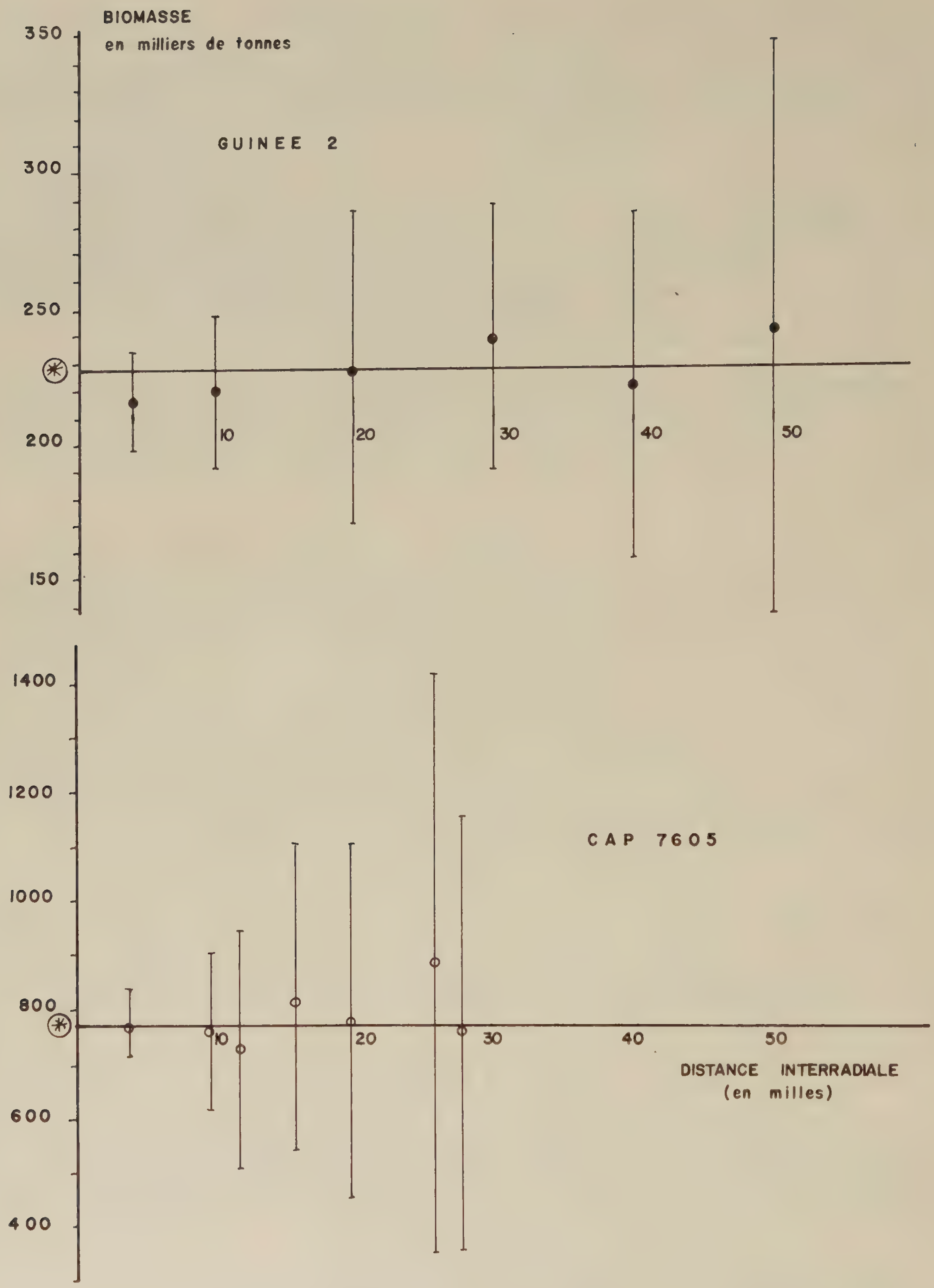

Fig. 7: Estimation de la biomasse totale pour différents niveaux d'échantillonnage.
⊛ valeur réelle (total simulé)

Dans un deuxième temps nous avons donc simulé un autre type de prospection plus proche des exigences de la réalité (Fig. 5). Dans ce cas une première prospection est réalisée suivant un schéma régulier de radiales espacées de 10 milles, puis une prospection en dents de scie est effectuée à l'intérieur de la strate riche, afin d'en déterminer précisément les limites. Une fois délimité la strate riche, il n'y a en effect aucun empêchement logique à y parcourir une route désordonnée, puisque les ESDU sont indépendants à l'intérieur de la strate.

Il devient difficile dans ces conditions d'appliquer la méthode de calcul de la variance de Bazigos, aussi avons-nous effectué un calcul classique de la variance en prenant comme unité d'échantillonnage la radiale. La région a été découpée en trois sous-régions et la variance calculée pour chacune de ces sous-régions, avec le profil de campagne classique (radiales parallèles espacées de 10 milles) d'une part, puis avec la nouvelle stratification d'autre part. La variance dans ce dernier cas est à peu près la moitié de celle de la campagne témoin.

Il est hasardeux de comparer ce résultat avec celui des campagnes à radiales resserrées, la méthode de calcul étant distincte. Néanmoins la stratification fait gagner en précision par rapport à un schéma de prospection non stratifié, comme dans la simulation précédente, tout en étant logiquement et pratiquement plus satisfaisant. Enfin, si comme dans le cas précédent on se contente d'une radiale par 20 milles dans la zone pauvre, ce qui ne change pas la variance, ce schéma de campagne n'aura augmenté le trajet que d'une dizaine de milles par rapport à un échantillonnage régulier tous les dix milles.

Considérant maintenant l'ensemble des campagnes effectuées en Afrique de l'Ouest par l'ORSTOM à la lumière des informations apportées par cette étude, nous avons estimé grossièrement l'intervalle de confiance des résultats obtenus entre 1974 et 1979. Pour celà nous n'avons retenu comme source d'erreur que celles imputables à l'échantillonnage et au calcul de la constante d'intégration (calibration par la méthode de la cage d'après Johannesson et Losse, 1973), erreur sur la constante que nous avons estimé par ailleurs à 20% (Gerlotto et Stéquert, 1979).

La quasi totalité des campagnes s'est déroulée suivant le schéma classique des radiales parallèles, ayant un espacement proportionnel à la surface à couvrir et au temps imparti aux campagnes. Dans ces conditions, l'intervalle de confiance global des résultats (au seuil 5%) a varié suivant les campagnes entre 30 et 60%.

4. CONCLUSION

Tous les biologistes des pêches ayant dû un jour effectuer une campagne d'echo-intégration (et toujours en admettant qu'ils aient agi avec assez de précaution pour être certains de tous leurs résultats) se sont trouvés confrontés à deux phénomènes apparemment contradictoires mais à peu près constants:

- d'une part une variabilité individuelle des données importante, en particulier la quasi-impossibilité de retrouver les mêmes valeurs aux mêmes endroits;

- d'autre part une remarquable cohérence et (au fil des ans) une grande constance des résultats globaux.

Nous espérons avoir aidé à démontrer dans cette étude que ces deux phénomènes étaient cependant compatibles dans la mesure où l'on se rend compte que les valeurs de densité entre deux ESDU obéissent à une loi générale permettant de regrouper les densités en strates cohérentes, mais que cette loi intègre un paramètre apparemment aléatoire qui, à l'intérieur d'une strate, est le principal responsable de la variabilité des données.

De ceci nous pouvons tirer trois conclusions.

i) Le paramètre aléatoire que nous avons observé est considéré comme tel dans l'état actuel de nos connaissances et à l'échelle où nous travaillons, mais il s'agit probablement d'une loi de fluctuation des densités dans le temps, l'exploration se déroulant sur un milieu éminemment mobile.

ii) Il serait également très intéressant, à partir de là, de définir les dimensions idéales d'un ESDU: les observations des données montrent un effet que l'autocorrélation des mesures existe jusqu'à une certaine distance. Deux émissions successives sont hautement corrélées, cette corrélation diminue rapidement et nous avons vu qu'avec une dimension d'ESDU de 2 milles, elle n'existait pratiquement plus. Une mesure de la plus petite longueur d'ESDU "indépendante" reste à faire. Des calculs provisoires sur des ESDU de 1 mille semblent montrer qu'eux aussi sont indépendants.

iii) Il devient également possible, ou du moins plus facile, de définir une strate: il s'agit de la région à l'intérieur de laquelle les variations des ESDU sur la portion de radiale peuvent être considérés comme aléatoires. A partir de là on pourrait vérifier si les strates choisies sont cohérentes ou non.

Si l'on considère maintenant l'application de ces observations aux campagnes réelles, deux points sont à noter: tout d'abord, on peut conclure que le point le plus important, celui qui domine la précision des mesures, est la connaissance précise des limites des strates. Ce sont ces enveloppes qui par leur juste délimitation permettent de réduire la variance. La mesure de la valeur moyenne de la densité est en effet bien plus facile à connaître avec une bonne précision. Dans ces conditions le plan de campagne idéal est probablement le suivant: un réseau régulier assez lâche dans une première étape, qui donnera les densités des zones peu peuplées et la localisation des zones riches afin d'en déterminer la densité et les limites.

Le deuxieme point est une observation plus générale sur l'écho-intégration. Les résultats que nous avons déjà obtenus, en décidant arbitrairement d'un échantillonnage, ont donné une incertitude de 30 à 60%, ce qui est déjà supérieur comme précision à ce que peuvent donner la plupart des autres méthodes d'évaluation des populations. Cette imprécision peut encore être diminuée quelque peu par un échanillonnage adéquat, mais atteindra de toutes façon sa limite assez vitre à cause de la mobilité de la population échantillonnée. En revanche il est un point qui lui doit être approfondi car c'est à l'heure actuelle le facteur limitant principal: il s'agit des risques de biais et d'erreurs dont foisonne la méthodologie de l'écho-intégration. Qu'il s'agisse du fonctionnement correct de l'équipement, de la mesure des bancs de poissons, des conséquence du comportement du poisson, de la calibration, etc., toute erreur à ces niveaux prend en général la forme d'un biais impossible à rattraper et risque de fausser gravement les résultats. Notons à ce propos que l'apparition du matériel de seconde génération (écho-sondeurs et écho-intégrateurs) pourra éliminer un nombre appréciable de ces risques.

RANDOM ERRORS OF ACOUSTIC FISH ABUNDANCE ESTIMATES IN RELATION TO THE SURVEY GRID DENSITY APPLIED

By

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ABSTRACT

Repeated echo integration surveys using a dense survey grid system were made in areas where the effect of fish migration was assumed to be insignificant. Indices for total fish abundance representing different survey grid densities were calculated by using observations along all the courselines, every second courseline, every third courseline and so on. The "degree of coverage" of an area was defined as the ratio between "sailed" distance and the square root of the total area covered. Coefficients of variation of the abundance indices were calculated for each degree of coverage. Observations and results for different species, areas and seasons are compared and discussed, and a power curve fit between the coefficient of variation and the degree of coverage for all the observations is presented.

RESUME

Des échoprospections répétées en utilisant des radiales de prospection serrées ont été effectuées dans des zones où les migrations des poissons étaient considérées comme négligeables. On a calculé des indices d'abondance du poisson pour différents espacements de radiales en utilisant les données collectées sur toutes les radiales, une radiale sur deux, une radiale sur trois, etc. Le "degré de couverture" d'une zone a été défini comme étant le rapport entre la distance parcourue et la racine carrée de la surface totale de la zone couverte. Les coefficients de variation des indices d'abondance ont été calculés pour chaque degré de couverture. Les observations et résultats concernant différentes espèces, zones et saisons sont comparés et discutés. Une fonction puissance liant le coefficient de variation et le degré de couverture est présentée pour toutes les observations effectuées.

1. INTRODUCTION

When acoustic estimates of fish biomass are used for management purposes, the lack of proper variance estimates are often felt. Some authors have analyzed various sources of random errors associated with acoustic estimates of fish densities (Bodholt, 1977; Lozow, 1977; Ehrenberg and Lytle, 1977; Moose and Ehrenberg, 1971; Aksland, 1976). However, there is not yet developed any efficient variance estimator which applies data collected during a survey. Some ideas about the random errors may be gained by considering repeated surveys on a presumably constant fish biomass as for instance those reported by Johanneson and Losse (1977) and Blindheim and Nakken (1971).

This work presents empirical variances for such repeated surveys. By normalizing the data, the variance is studied as a function of the degree of coverage.

2. MATERIAL AND METHODS

Results from a number of surveys are analyzed. Table 1 summarizes important data about the surveys. Small (5-30 cm) pelagic fish which is schooling by day and scattered at night dominated during all surveys except those from Lofoten. Figure 1 shows the location of the survey areas. Figure 2 and 3 show examples of survey grids. In all areas, except the Barents Sea, repeated coverages were made within few days. For each coverage an average echo integrator value representing fish was calculated. This average was calculated by applying only the values obtained within the observed fish distribution area. When the coverage was uneven (in Lindåspollene), average values were

Table 1. Key data about the surveys.

Name of area	Dominating fish species	Size of covered area (n.mile)^2	No. of survey-series	No. of "dense" coverages within each series	Time
1) Fjellangervågen	Sprat	.17	1	4	Sep.77
1) Lindåspollen	Herring	1.0	2	2-11	Sep.77,Mar.78
1) Outer Eidfjord	Sprat	13	2	5- 7	Feb.-Mar.78
1) Samlafjord	"	16	3	4- 8	Jan.-Mar.78
1) Nordfjord	"	22	1	9	Feb.78
1) Eidfjord	"	25	3	2- 6	Oct.77-Jan.78
2) Lofoten	Cod	120	1	6	Mar.71
3) Barents Sea	Capelin	∿50 000	5	1	Sep.-Oct.each year from 74 to 78

1)The surveys are further described by Aglen (1982)

2) " " " " " " Blindheim and Nakken (1971)

3) " " " " " " Buzeta *et al.*, (1975), Dommasnes, Nakken and Røttingen (1976), Dommasnes and Røttingen (1977), Monstad and Røttingen (1977) and Dommasnes, Loeng and Monstad (1979).

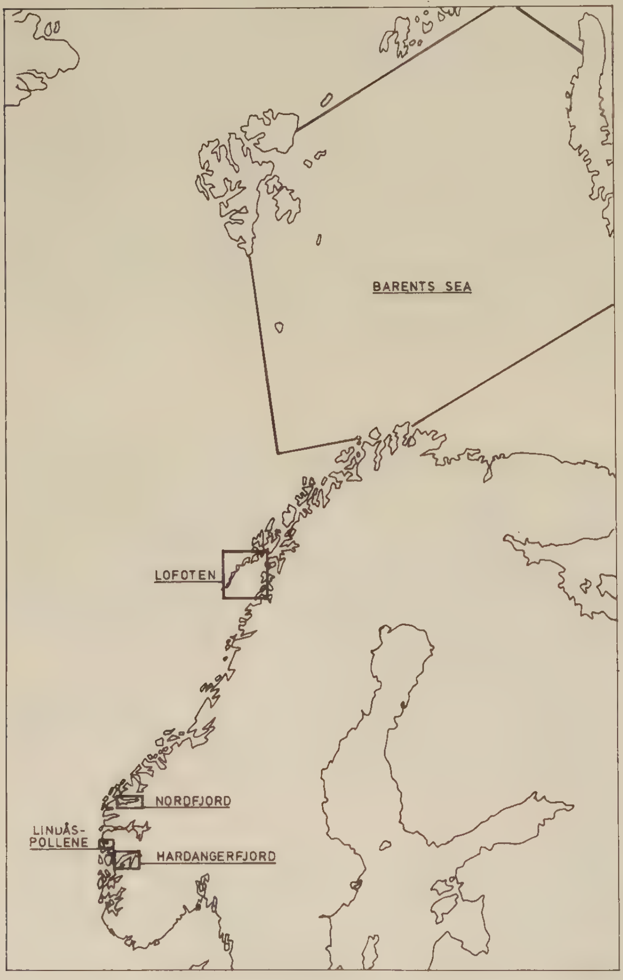

Fig. 1. Location of survey areas. Samlafjord and Eidfjord are parts of Hardangerfjord. Fjellangervågen is part of Lindåspollene.

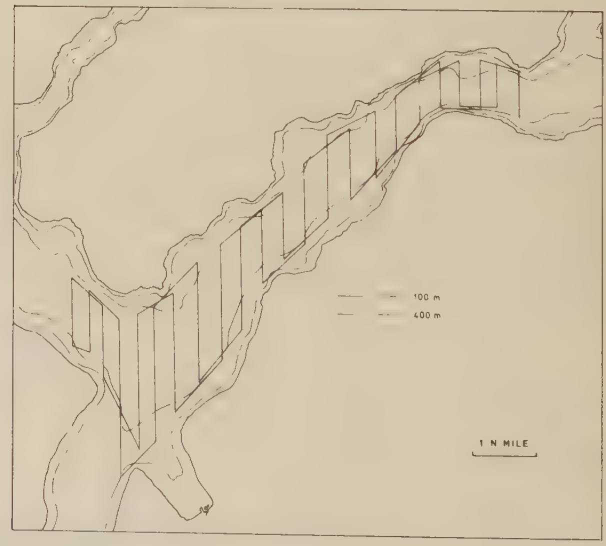

Fig 2. Typical survey grid applied in Eidfjord.

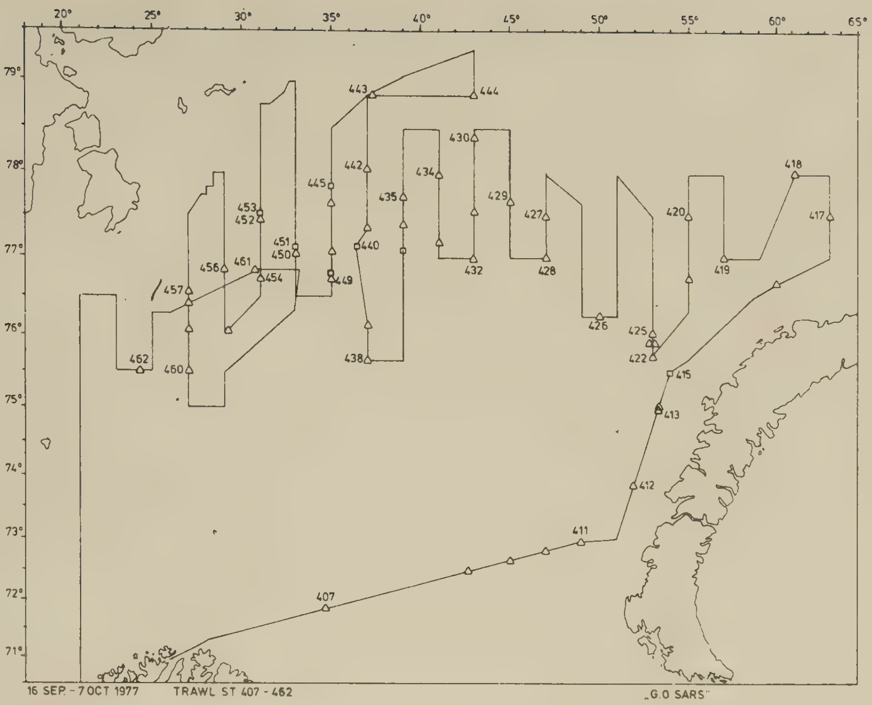

Fig. 3. Typical survey grid applied in the Barents Sea.

calculated within subareas and an area-weighted total average was calculated. This average integrator value from each survey is in the rest of the paper called the abundance index, for which the symbol t is used. In the Barents Sea only values obtained along 16 north-south going courselines were applied (Fig. 3). From each original coverage indices for "looser" coverages were obtained by applying observations from every second courseline, every third courseline, and so on.

Detailed informations about the acoustic equipment is given by Aglen (1982). The equipment used in the fjords and fjord inlet had a rather unfavourable threshold setting leading to systematic differences between values obtained during day and night. However, in these small areas it was possible to make separate coverages during day and night and the results are treated separately.

For each series of n similar coverages made on presumably the same fish consentrations the coefficient of variation; $SD\ t/\bar{t}$, was calculated. This is independent of the units of t and is therefore useful for comparison of the variability observed during various series of coverages. For the same reason it is desirable to define a degree of coverage which is independent of units. The definition choosen was $N/\sqrt{A}$ where N is the total length (nautical miles) of the courselines falling inside the fish distribution area and A (square nautical miles) is the part of the fish distribution area intended to be covered by the survey grid.

3. RESULTS

The degree of coverage and the coefficient of variation for the various series of coverages are shown in Table 2 and 3. In Table 2, which is the results from fjords and inlet, day and night values are treated separately.

Most observations were obtained in the fjords and in the Barents Sea. Linear regressions made on log-transformed data gave

$\ln (SD\ t/\bar{t}) = -0.73 - 0.46 \ln (N/\sqrt{A})$, $r = -0.62$ in the fjords during night,
$\ln (SD\ t/\bar{t}) = -0.53 - 0.43 \ln (N/\sqrt{A})$, $r = -0.33$ in the fjords during day
$\ln (SD\ t/\bar{t}) = -0.71 - 0.69 \ln (N/\sqrt{A})$, $r = -0.67$ in the Barents Sea.
$\ln (SD\ t/\bar{t}) = -0.69 - 0.41 \ln (N/\sqrt{A})$, $r = -0.44$ for all observations.
(r is the correlation coefficient).

Table 2. Degree of coverage ($N/\sqrt{A}$), coefficient of variation ($SD\ t/\bar{t}$) and the number of coverages (n) of each series of surveys in inlet and fjords.

Name and size (A) of area, time	$N/\sqrt{A}$	NIGHT n	NIGHT $\frac{SDt}{\bar{t}}$	DAY n	DAY $\frac{SDt}{\bar{t}}$
Fjellangervågen	6.5	4	.18		
A=0.17 sq.n.mile	3.3	7	.21		
Sep.-77	1.6	15	.23		
Lindåspollene					
A=1.0 sq.n.mile	8.0	1	-	1	-
Sep./Oct.-77	4.0	2	.09	2	.43
Lindåspollene					
A=1.0 sq.n.mile	8.0	4	.39	6	.61
Mar.-78	4.0	8	.52	13	.58
Eidfjord	5.0	2	.68	7	.37
A=25.1 sq.n.mile	3.0	5	.51	12	.53
Oct.-77	2.0	7	.47	18	.75
	1.0	14	.67	36	.95
Eidfjord	10.6	2	.12		
A=25.1 sq.n.mile	5.2	4	.09		
Nov.-77	2.6	8	.20		
	1.4	16	.36		
Eidfjord	10.0	4	.13	2	.51
A=25.1 sq.n.mile	5.0	8	.25	4	.41
Jan.-78	2.4	16	.69	8	.74
Samlafjord	5.8	4	.12	1	-
A=27.3 sq.n.mile	3.1	6	.12	2	.38
Jan.-78	1.5	12	.32	4	.66
Nordfjord	11.1	5	.16	4	.40
A=21.6 sq.n.mile	5.6	10	.25	8	.61
Feb.-78	2.8	20	.35	16	.91
Outer Eidfjord	8.2	2	.36	3	.20
A=13.1 sq.n.mile	4.2	4	.30	6	.20
Feb.-78	2.8	6	.30	9	.31
Samlafjord	5.0	6	.17	2	.01
A=15.6 sq.n.mile	2.5	12	.20	4	.24
Feb.-78	1.8	18	.31	8	.14
Samlafjord	6.8	4	.22		
A=15.6 sq.n.mile	3.8	7	.24		
Mar.-78	2.0	12	.38		
	1.0	24	.47		
Outer Eidfjord	15.5	3	.16	4	.17
A=13.1 sq.n.mile	7.7	7	.24	7	.29
Mar.-78	3.9	12	.26	12	.33
	1.9	12	.27	14	.43
	1.1	16	.55	16	.60

Table 3. Degree of coverage ($N/\sqrt{A}$), coefficient of variation ($SD\ t/\bar{t}$), and the number of coverages (n) of the surveys in Lofoten and the Barents Sea.

Name and size (A) of area, time	$N/\sqrt{A}$	n	$\frac{SDt}{\bar{t}}$
Lofoten	9.6	6	.30
A = 119 sq.n.m.	4.8	12	.36
Mar. 1971	3.2	18	.42
	2.4	24	.42
	1.9	30	.59
Barents Sea	5.5	2	.04
A = 62540 sq.n.m.	2.8	4	.13
Sep. - Oct. 1974	1.4	8	.29
	.7	16	.40
Barents Sea	5.1	2	.18
A = 57250 sq.n.m.	2.6	4	.25
Sep. - Oct. 1975	1.3	8	.20
	.6	16	.43
Barents Sea	5.3	2	.20
A = 54210 sq.n.m.	2.7	4	.30
Sep. - Oct. 1976	1.3	8	.50
	.7	16	.62
Barents Sea	4.7	2	.10
A = 40590 sq.n.m.	2.4	4	.42
Sep. - Oct. 1977	1.2	8	.41
	.6	16	.72
Barents Sea	4.9	2	.48
A = 57600 sq.n.m.	2.5	4	.74
Sep. - Oct. 1978	1.2	8	.89
	.6	16	1.20

4. DISCUSSION

The results show a general tendency of decreasing coefficient of variation with increasing degree of coverage. $SD\ t/\bar{t}$ will approach infinity when $N/\sqrt{A}$ approaches zero, while it probably will approach an asymptotic minimum level at very high values of $N/\sqrt{A}$. This situation may be properly described by a power curve fit.

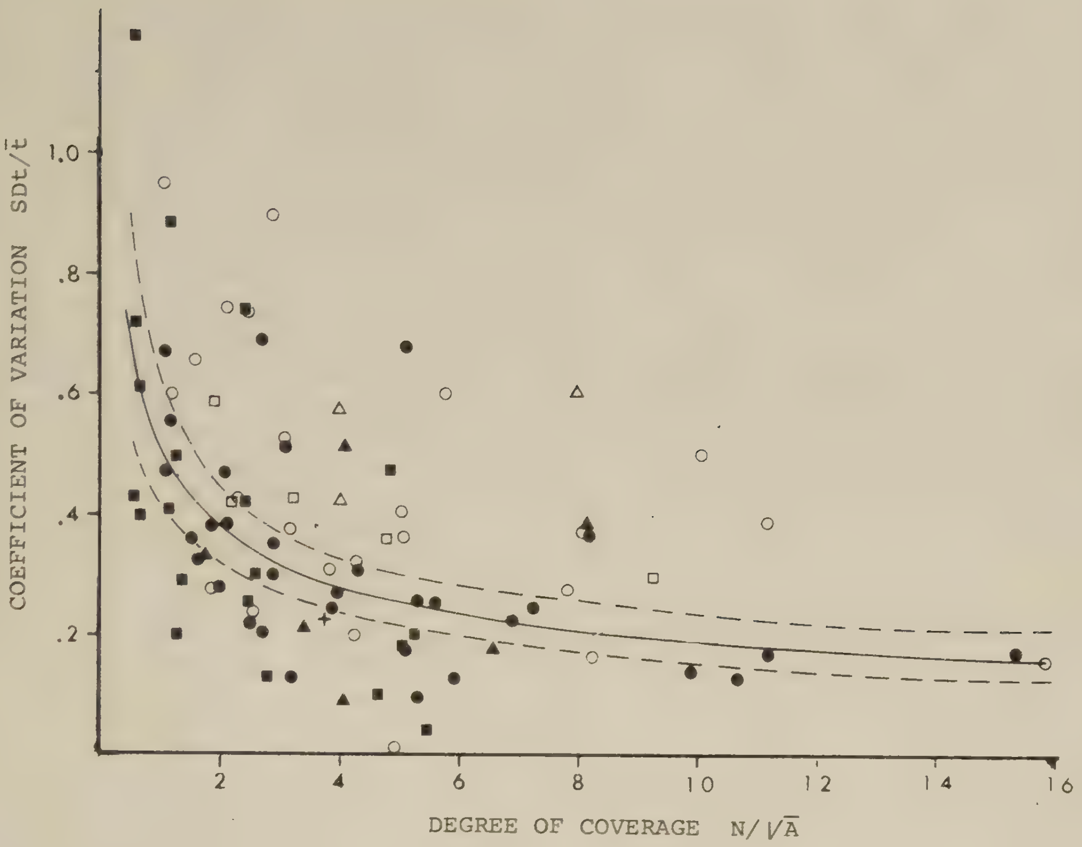

Fig. 4. Corresponding values of degree of coverage and coefficient of variation for all areas.

—— Regression line
--- Confidence belt for the regression line
● Samlafjord, Eidfjord and Nordfjord during night
○ Samlafjord, Eidfjord and Nordfjord during day
● Lindåspollene during night
○ Lindåspollene during day
□ Lofoten
■ Barents Sea
+ Johannesson and Losse (1977).

Tests given by Zar (1974) lead to the conclusion that, at 5% significance level, all the regressions shown have a significant negative correlation coefficient and that none of the regressions have a significant different slope or interception compared to the others. The regression line based on all the observations is shown in Figure 4 together with the confidence belt of the regression line. In addition one point representing 4 repeated surveys made by Johannesson and Losse (1977) is shown.

There are no evidences of clear differences between results from different areas, even when comparing the 1 square nautical mile Lindåspollene with the 50 000 square nautical mile survey area in the Barents Sea. This confirms that the applied definition of the degree of coverage is convinient for evaluation of survey effort. However, the observations are very scattered, because the precision is influenced by other factors than the coverage. The uniformity of the fish distribution seems to be the most important factor.

The results given in Table 2 illustrates that improved precision may be easier obtained by finding the time of the year giving the most suitable fish distribution than by simply increasing the survey effort.

Intuitively one would expect a higher variance of the estimates obtained on fish schools (during daytime) compared to the variance of estimates obtained on scattering layers (during night). However, the results do not show any significant difference. The difference may be masked by the threshold effect which was rather high during the surveys in the inlet and fjords. This effect introduces an extra variance during night if there are variations in the volume density of fish (Aglen, 1982). This variance is likely to be independent of the degree of coverage. Moose and Ehrenberg (1971) and Bodholt (1977) discuss other sources of variation which are independent of the degree of coverage. These sources of variance will define the asymptotic minimum level for the coefficient of variation when plotted against the degree of coverage.

It is important to note that the results discussed represent relative abundance indices and do not include systematic errors of the absolute estimate. When fish target strength is influenced by the passage of a survey vessel (Olsen, 1979), and average target strengths estimated from cage calibrations are directly used for abundance estimation, systematic errors may be much more serious than random errors.

ON PLANNING AN ECHO SURVEY

by

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ABSTRACT

Methods for the calculation of a grid of searching tracks of an echo survey are suggested. The calculations are based on the well-known theses of the theory of searching. The echo survey is regarded as a process of regular hydroacoustic exploration of the biological resources in the given area and is equal to the stationary Poisson process. The equations for calculating zigzag and right-angled schemes of tracks are given. To evaluate the degree of completeness of the area inspection the notation of the exploration probability is introduced.

The suggested substantiation and calculation of searching tracks for an echo survey is an attempt to regulate the process of hydroacoustic exploration of the different areas alloted for echo surveys within the framework of mathematical ratios.

RESUME

La méthode de calcul du réseau des itinéraires de la prospection écho-métrique est proposée. Le calcul peut être basé sur les thèses connues de la théorie de recherches. La prospection écho-métrique comme le processus de l'examen hydroacoustique régulier de ressources biologiques de la région examinée est égale à la distribution stationnaire du poisson. Les formules de calcul pour les schémas des itinéraires rectangulaire et zigzagué sont presentées. Pour évaluer le degré de l'exploration de la surface de la région de l'écho-prospection la notion de probabilité de détection est introduite.

Le fondement et le calcul du réseau des itinéraires proposés représentent une certaine tentative de régler le processus de recherches hydroacoustiques des régions différentes de l'écho-prospection dans les cadres des proportions mathématiques.

List of Symbols

P_e - probability of exploration of an echo survey area

t_e, hour - time of exploration of an echo survey area

D, nautical miles - horizontal extension of fish aggregations

V_s, knots - velocity of a ship

V_f, knots - horizontal velocity of fish aggregation

S_a, square miles - size of area alloted for an echo survey

S_e, square miles - area of elementary exploration

t_e, hour - time of elementary exploration

l_r, miles - length of track

l_n, miles - length of distance where the ship changes tracks

l, mile - inter-track distance

t_r, hours - time at which the ship stays on the track

α, degree - angle between track lines and inter-track distance of the ship

γ, $\frac{1}{\text{hour}}$ - intensity of exploration

S_n, square mile - size of an area "observed" by the ship at a certain time interval

U - potential of detection

1. INTRODUCTION

The tactics of condition of an echo survey can be based on the well-known theses of the theory of searching (1). There is a close agreement between the echo survey and searching. Both types represent directed exploration, in our case, of the oceanic environment. However, the aims of exploration are different. While the searching is aimed at detection and recording of an object, the aim of the echo survey is the quantitative recording of the number of the objects which are present within the surveyed area. Sometimes, the objectives of the echo survey and searching are concurred (when the area is not investigated).

Echo surveys are usually conducted by a single ship. This ship explores the given area by means of random or regular tracks to reveal the boundaries of distribution and to estimate the biomass of fish aggregations. The validity of quantitative estimates along with other factors depends mainly on the degree of completeness of the area inspection. It is evident that the area may be considered to be completely investigated when all fish aggregations appear in the zone of hydroacoustic contact during the echo survey. This condition is rather difficult, if possible at all, to observe for a single ship.

In fact, the complete exploration of the area necessitates a dense track grid which may result in the large expenditures of time, and thus, the requirements for a quick estimate of the biological resources won't be met. Besides, the financial expenses may appear to be too large. So, practically, it is important both to determine, on the basis of quantitative relations, the major parameters of a real scheme for conduction of an echo survey and to introduce an efficiency coefficient.

2. METHODS

The method of calculation of a grid of tracks for the echo survey may be considered as the first variant for solution of this task. From a classification of mathematical models in searching theory the suggested calculation is based on the determination of the exploration process as the random Markov's type process for which a flow of events is the succession in detections of an object at random time periods. During the echo-survey the number of aggregations recorded during a given period of time is independent of the number of detections in other periods, excluding the coverage of the given one, i.e. a flow of detections has no aftereffect. However, the probability of detection of two aggregations at the same period of time is negligible compared to the probability of detection of a single aggregation. This property called ordinary one means that the aggregations are recorded by ones and not by twos, threes, etc. The flow of detections during the echo survey is stationary because the probability of appearance of one or another detection in the time period Δt depends only on its size and is independent of location on the time axis. Thus, the echo survey may be regarded as the stationary Poisson process, provided that this echo survey having the above-mentioned properties is outlined as a process of regular hydroacoustic exploration of biological resources in a given area.

Then, similar to the equation of detection probability (deduced in the searching theory) it should be written as

$$P_m = \frac{U^m}{m!} e^{-U} \qquad (1)$$

where $U = \gamma t_e$ is the Poisson parameter which in this case denotes the methematical expectation of number of fish aggregation detections in the given area (over the time t_e) and is called the detection potential in the searching theory

$m = 0,1,2...$ is integral nonnegative values of random quantity corresponding to different numbers of detections in the given area (over the time t_e)

γ is mean number of detections over a time period (intensity of a flow of detections). For the stationary Poisson flow $\gamma = \text{const}$.

The equation (1) expresses the Poisson's law for distribution of the equally fixed detection number m over the exploration, time t_e. However, for practical purposes it would be sufficient to determine the probability of appearance of detection number not less than the fixed value, for example, no less than one. This probability may be simply determined as the probability of contrary event

$$P_{m\geq 1} = 1 - P_{m=0} \qquad (2)$$

where $P_{m=0} = e^{-U}$

then $$P_{m\geq 1} = 1 - e^{-U} \qquad (3)$$

The resultant probability of even one detection of an object during the exploration of a given area will be called the probability of area exploration and further abbreviated P_e. In this case fish aggregations with clearly pronounced boundaries on the echogram are recognized as the objects of detection. Thus, the fish concentration for which the echo-record has no intervals of over 5 minutes is arbitrarily adopted as one fish aggregation. Such interval approximately corresponds to the horizontal distances of 1000 ÷1500 m between the aggregations at the usual ship velocity of 7 ÷10 knots during the echo survey. Thus was practically calculated the number of aggregations M observed during the echo survey.

For planning of exploration probability the value of horizontal extension D of fish aggregations which are indicative of the surveyed area should be taken into account. This value as well as mathematical expectation of aggregation extensions is calculated by means of a standard method based on the analyses of the echograms from commercial and searching ships operated in the given area.

As reference points the following conditions must be observed for calculation of a track grid:

- a flow of detected fish aggregations is characterized by stationary Poisson distribution;
- a fish aggregation with the mean statistical horizontal extension of D miles is taken to be object of searching or echo survey;
- the width of the hydroacoustic contact (detection) zone is assumed to be D;
- the velocity of the ship V_s is three or more times the horizontal velocity of fish aggregations which allows to consider the latter immobile while the ship changes tracks;
- echo survey is made along parallel tracks.

Theoretically, the above conditions make it possible to organize regular searching so that during the hydroacoustic exploration of the environment each location is covered in the detection zone once, excluding repeated coverage of these locations before the entire area is investigated.

The above-mentioned premises are expected to operate under the conditions of ideal behaviour of fish aggregations, therefore, they are adopted in first approximation as adequate and necessary for operational calculations in planning.

In fact, the vast area for conduction of an echo survey by a single ship should result in errors in biomass estimates since both the track length and distance between tracks are regulated by the size of the area and time alloted for area exploration.

So, with the increase in the track length and distance the possibility of omission in the echo-record of the mobile aggregation due to its shifting when the ship changes in the tracks is risen. For the same reason with the decrease in the track length and inter-track distance the possibility of repeated records of the same aggregation is increased.

The difficulties faced during the investigation of vast areas and limited time alloted for conduction of a reliable echo survey necessitate the search of an optimum decision.

The present methods of calculation of the grid of tracks may be considered as the first attempt to optimization based on usage of a characteristic of probability of exploration P_e. In fact, this characteristic determines the criterion of investigation efficiency, and, added to such parameters as the size of the area S_a and exploration time t_e is used for the fundamental calculation in planning of the echo survey.

When a parallel track scheme is selected the right-angled or zigzag grid of tracks is usually made for conduction of the echo survey (Figs. 1a, b). In both types, the calculation is based on an assumption that the elementary exploration of the area S_e is made over the t_e time.

As is evident from Figs. 2 and 3 the elementary area is constructed by means of plotting the lines of tracks l_r and inter-track distance l_n added up to a route l_e of a ship during one exploration. The size l of inter-track distance is selected and the width of the zone "observed" by a ship assumed to be equal D - the size of the mean statistical extension of aggregations.

Thus, the area S_e of the elementary exploration (ABCE contour) is the sum of areas of the "observed" and "unobserved" zones.

From geometrical constructions in Figs. 2 and 3

$$S_e = (l_r + D)\, l, \text{ sq.miles} \tag{4}$$

where t_r is the time of a ship staying on a track, hours

l is inter-track distance, miles

$$l_r = v_s t_r \text{ is the length of track, miles} \tag{5}$$

The time of elementary exploration is

$$t_e = \frac{l_r + l_n}{v_s}, \text{ hour} \tag{6}$$

where l_n is the distance where the ship changes tracks

For the zigzag tracks:

$$l_n = \sqrt{l_r^2 + l^2} \tag{7}$$

or

$$l_n = \frac{l}{\sin\alpha} \tag{8}$$

α is the angle between track lines and inter-track distance of a ship.

For the right-angled tracks:

$$l_n = l$$

The exploration intensity (or intensity of a flow of detections) can be calculated as the relation of the area observed by an observer over a time period and the area of "unobserved" zone:

$$\gamma = \frac{DV_s}{S_e - S_{ne}} \quad , \quad \frac{1}{\text{hour}} \tag{9}$$

where S_{ne} is the area observed over a time of elementary exploration

DV_s is the area observed over an hour

It is evident that for the suggested determinate model of exploration area S_e, only its part being observed once, the exploration intensity as a number of detections over a time period depends on the size of area of "unobserved" zone. In other words, the greater area of the unobserved zone, the lesser number of possible detections over a time period.

For the right-angled scheme

$$S_{nr} = DV_s t_e = D(l_r + 1) = Dl_e \tag{10}$$

$$l_e = l_r + 1 \tag{11}$$

where l_e is the length of a ship distance over one exploration.

For the zigzag scheme

$$S_{nz} = (l_r + D)\, D + \frac{D\ (1-D)}{\sin \gamma} =$$

$$= Dl_e + D^2\ (1 - \frac{l_n}{l}) \tag{12}$$

Making substantion of the values S_e and S_n from equations (4) and (10) or (12) in the equation (9) we obtain for the above mentioned schemes of tracks, respectively.

$$\gamma n = \frac{V_s}{l_r(1/D-1)} \quad , \quad \frac{1}{\text{hour}} \tag{13}$$

$$\gamma z = \frac{V_s}{(1/D-D)\ (l_r + D-Dl_n 7 l)} \quad , \quad \frac{1}{\text{hour}} \tag{14}$$

As is evident from the equation (12) the given equation transforms to the form (10) provided $\sin\alpha=1$, as well as the equation (14) transforms to the form (13) when $l_n = 1$.

Analysis of the values of exploration intensity using the equations (9), (13) and (14) indicates that if the observed S_n and total area S_e of elementary exploration are equal or, which is the same, when the inter-track length l and statistical mean extension D of observed aggregations are equal, the value of intensity becomes limitary and meaningless ($\gamma=\infty$) within the framework of the selected scheme of tracks. It is clear that the limiting case corresponds to the value of probability of exploration P_e equal to a unit.

Probability of elementary exploration of the area is expressed

$$P_e = 1 - e^{-\gamma t_e} \tag{15}$$

or

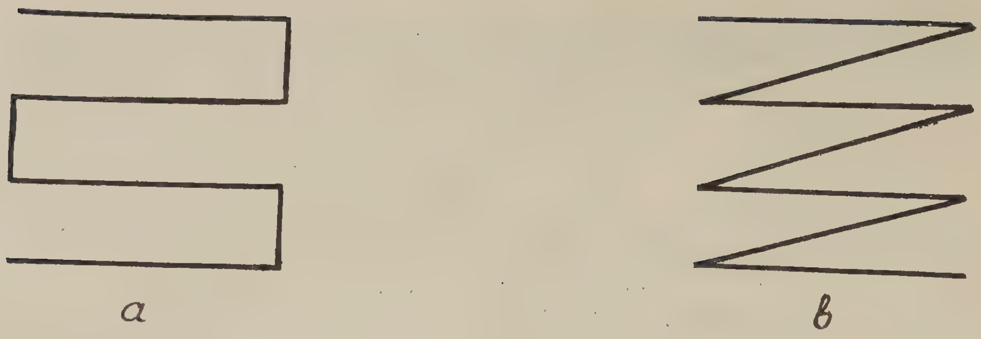

Fig. 1. Right-angled (a) and zigzag (b) scheme of tracks.

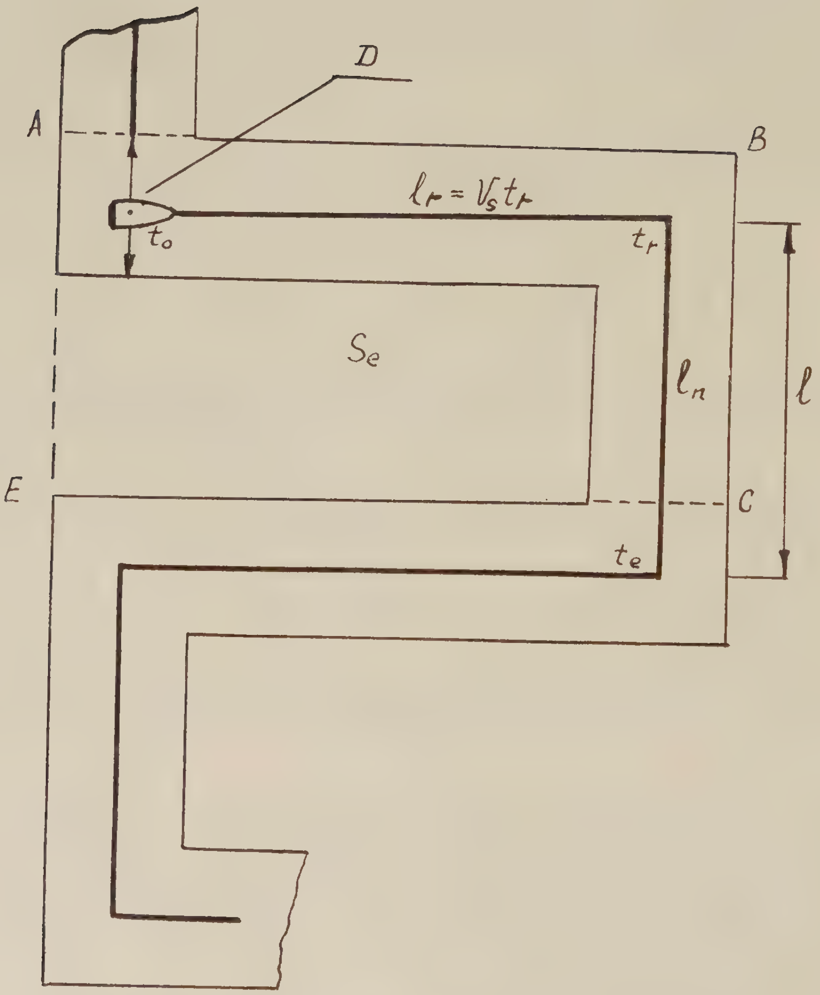

Fig. 2. Right-angled scheme of elementary exploration of the area S_e over the time t_e.

$$P_e = 1 - e^{-U_e}$$

where γ takes one or another value depending on a scheme of tracks;

U_e is the detection potential for the elementary exploration.

It is known that in the homogeneous field the probability P_e for elementary exploration will determine the probability for the size of the entire explored area alloted for the echo survey and then the calculation of a track grid reduces to the determination of the parameters of elementary cycle of exploration.

As the probability P_e defines the quantitative efficiency of area exploration the maximization of this criterion should be revealed.

The probability $P_e \to 1$ provided $\gamma \to \infty$ or $t_e \to \infty$. As a whole, the absolute value of power e, i.e. the potential of detection $|U_e| = \gamma t_e$, must be tended to infinity.

Therefore, the maximization of probability reduces to maximization of potential of detection.

It should be also noted that the potential of detection is the product of parameters related within the framework of equations (6), (13), (14).

So, for further determination of boundary conditions of U_e, its value should be first represented in an expanded form, i.e. by means of parameters of a scheme of tracks.

For this the zigzag scheme of tracks which is the most general case should be taken, i.e.

$$U_e = \gamma_z t_e = \frac{V_s t_a}{(l/D-1)\ (l_r + D-Dl_n/l)}$$

by substantion of t_e from equation (6) and taking into account equation (8)

$$U_e = \frac{l_r + l_n}{(l/D-1)\ (l_r + D-Dl_n/l)}$$

This expression in a closed form is represented as a product of two factors

$$U_e = \frac{1}{l/D-1} \cdot \frac{l_r + l_n}{l_r + D(1-l_n/l)} \qquad (16)$$

and the significance of each factor in the value U_e is evaluated. As it was mentioned above, the equality l=D is the limit for the existence of the suggested model of tracks. In this case, the factor

$$\frac{1}{l/D - 1} = \infty$$

and the value $U = \infty$, which corresponds to $P_e = 1$.

Thus the limits of value $\frac{l}{D}$ restrict the interval from 1 to ∞, i.e. the value $\frac{l}{D}$ cannot be below 1.

To reveal the limits of variation of second factor of the equation (16) its extremums at the extreme $\alpha = 0^\circ$ and 90° should be first calculated by representation of the factor in the form

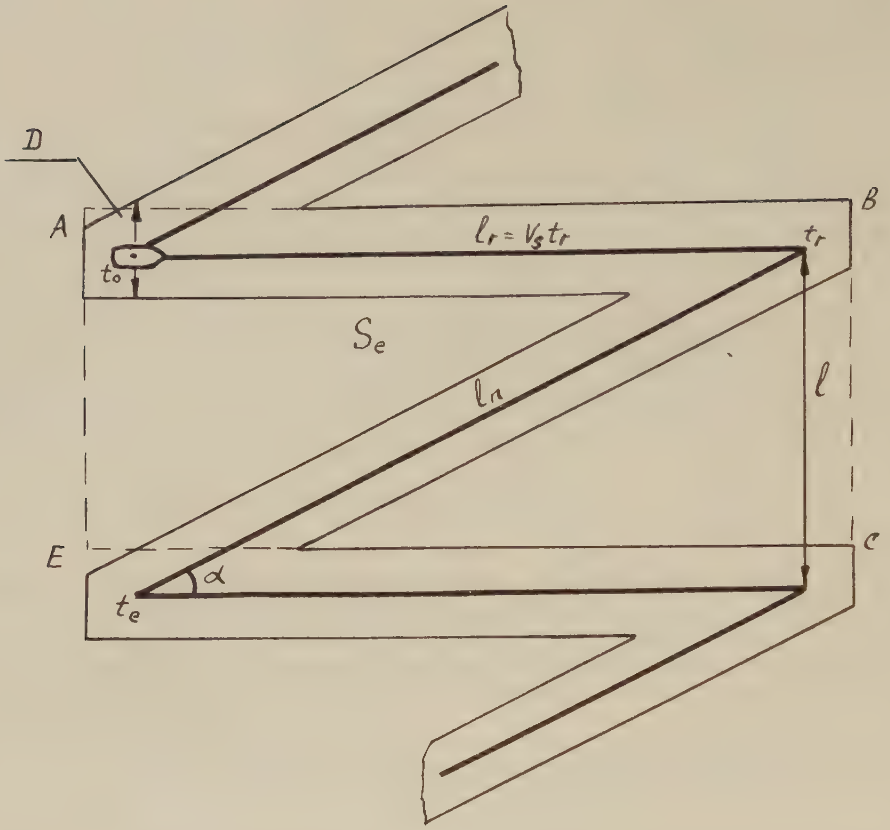

Fig. 3. Zigzag scheme of elementary exploration of the area S_e over the time t_e.

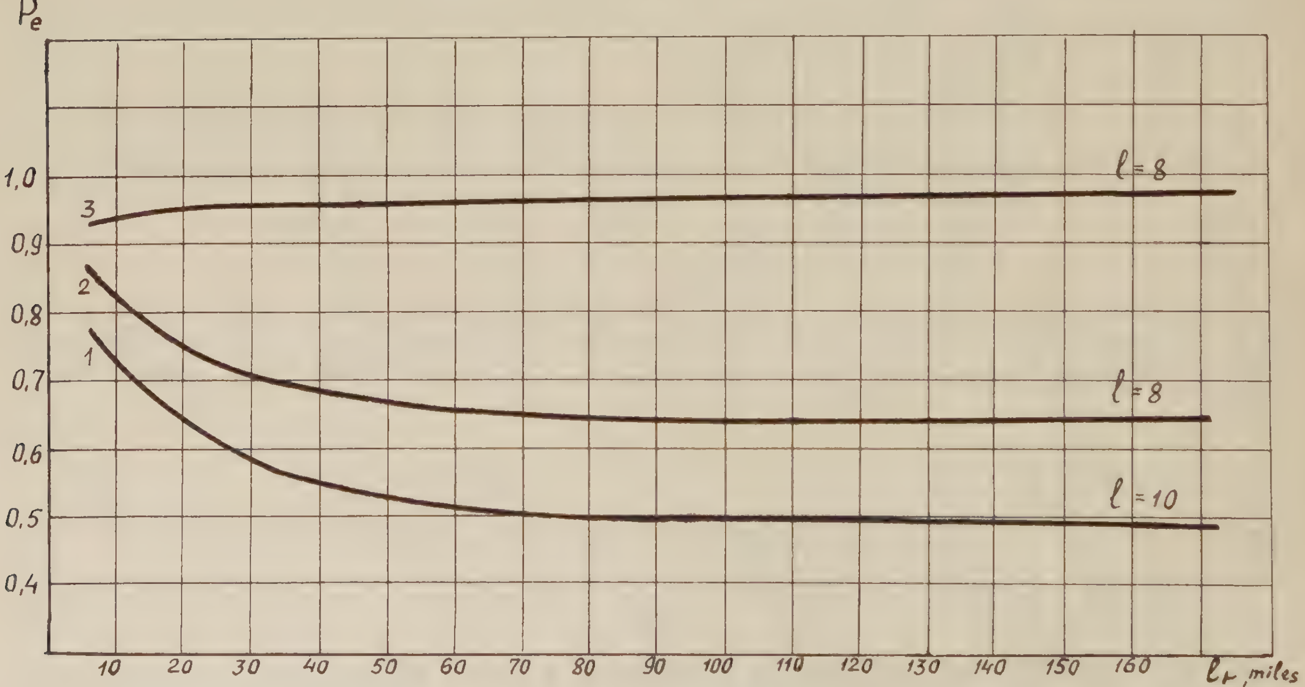

Fig. 4. Graph for determination of probability of exploration depending on length of track ℓ_r at different ℓ 1,2 - right-angled scheme; 3 - zig-zag scheme.

$$\frac{l_r + l_n}{l_r + D(1-l_n/l)} = \frac{l_r + 1/\sin\alpha}{l_r + D(1-\csc\alpha)};$$

It is clear that at $\alpha=0$ the factor is equal to ∞ and at $\alpha=90^\circ$ its value is equal to

$$\frac{l_r + l}{l_r} = 1 + l/l_r$$

and is in conformity with the right-angled scheme of tracks for which the equation (16) is transformed to the form

$$U_e = \frac{1}{l/D - 1}(1 + l/l_r) \tag{17}$$

It is evident for real conditions that the value of potential of detection is always above 1. It is advisable to consider the variation U_e as well as P_e depending on the length of track l_r since the value of inter-track distance l is selected as a fixed one in relation with D. The dependence $P_e = f(l_r)$ plotted on the graph at the selected l, V_s and D makes it possible to optimize the selection of the length of track l_r and of the inter-track distance l in planning of an echo survey.

Fig. 4 exemplifies the graph of dependence of probability of detection and length of track for the right-angled and zigzag schemes of tracks. The calculations were made using the equations (6), (7), (13), (14) and (15). The following was fixed:

$D = 4$ miles

$l = 8$ and 10 miles

$V_s = 8$ knots

i.e. $\frac{l}{D} = 2$.

Practically, it is appropriate to use the equations (15) and (16) for calculation of the planned probability of exploration. The calculation is simplified if as in the given example the relation $l = 2D$ is selected as a fixed one. This relation usually corresponds to the real scheme of tracks. In this case the first factor of the equation (16) is equal to 1.

For planning of a concrete echo survey on the basis of the given area boundaries approximated by a rectangle the length of track l_r (one of the sizes of a rectangle) and inter-track distance l are preliminary selected.

Then, an assumption of selection of these parameters corresponded to the accepted scheme of tracks is verified: firstly, the velocity of the ship must be three or more times the horizontal velocity V_s of the fish aggregations, i.e.

$$V_s \gg V_f \tag{18}$$

and secondly, the distance l_f covered by the fish aggregation at the time t_e of the elementary exploration must be within the limits S_e and should not exceed the value $(l-D)$ in the worst case, i.e.

$$l_f \leq l-D \tag{19}$$

The case is considered to be the worst one if the vector of velocity of fish aggregation is perpendicular to the track lines.

Since $l_f = v_f t_e$, then by substitution of its value from equation (19)

$$l-D = v_f t_e$$

or taking into account $t_e = \frac{l_r + l_n}{V_s}$ the expression is obtained

$$\frac{1 - D}{V_f} = \frac{l_r + l_n}{v_s}$$

Using the expression the maximum allowable length of track at the given conditions is determined

$$l_{r\ max} = (1 - D)\frac{v_s}{v_f} - l_n \qquad (20)$$

For instance, if the parameters D=4, l=8, $v_s=8$, $v_f=0.25$ are given then-for the right-angled tracks $(l=l_n)$

$l_{r\ max} = 120$ miles
- for the zigzag tracks

l_r max = 112 miles $\alpha = 30^o$
l_r max = 117 miles $\alpha = 45^o$
l_r max = 119 miles $\alpha = 60^o$

Then, it is practically advisable to select from the graph of Fig. 4 the real pair of values l_r and l corresponded to the optimum probability of exploration P_e i.e. the conduction of a given echo survey is provided over the maximum short periods at the high exploration efficiency. As is clear from the graph the values of exploration probability for the zigzag grid of tracks are higher than that for the right-angled scheme. So, the zigzag scheme of tracks is usually applied during the echo surveys.

In planning of the echo survey it is sometimes necessary to solve the inverse problem: to determine time t_e required for conduction of an echo survey based on the fixed probability of exploration P_e and total size of the area S_a.

Such calculation can be easily made using the considered equations (3) and (9) at the selected parameters of a scheme of tracks:

$$t_e = \frac{-l_n (1-P_e)(S_a-S_n)}{DV_s} \qquad (21)$$

It is evident that the equation (21) may be used to determine the total size of area S_a over a given time t_e and probability of exploration P_e for planning of an echo survey.

DISCUSSION AND CONCLUSION

The considered substantiation and calculation of searching tracks for an echo survey is an attempt to regulate the process of hydroacoustic exploration of the marine area within the framework mathematical ratios. As it was aforementioned the ideal model of explored environment is adopted as the basis for calculation. Thus, the results of calculations should be considered as approximate, although they are necessary for determination of initial tactics for the conduction of an echo survey.

In our opinion, the suggested calculation methods will help to rationally approach the solution both of a research task aimed at the increase of the echo survey efficiency and of another task aimed at economical spending of means in planning of marine expeditions.

On the basis of the present methods the expected efficiency (probability of detection) of hydroacoustic evaluation of the given area as well as the required means (ship units, cost of searching time, etc.) may be calculated in advance.

As is evident from the considered calculation methods the time of operations cannot be fixed arbitrarily in planning of the echo surveys, and the parameters of echo surveys (size of area, time and probability of exploration) are the values correlated mathematically.

The considered methods used in the AtlantNIRO since 1978 proved to be useful in operational planning of echo surveys.

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APPENDIX I

PAPERS PRESENTED TO THE SYMPOSIUM NOT PUBLISHED IN THIS VOLUME

Paper No.	Authors	Title	Subsequent Publication
1	D.N. MacLennan S.T. Forbes	General principles	ICES [1/]
2	J.E. Blue	Physical calibration	ICES [1/]
3	L. Middtun	Fish and other organisms as acoustic targets	ICES [1/]
4	R. Shotton G.P. Bazigos	Survey design	ICES [1/]
5	L.M. Dickie R.G. Dowd P.R. Boudreau	An acoustic data logging system giving numerical information on demersal fish size and density	Canada [2/]
6	U. Buerkle	Acoustic target strenth of capelin in relation to their aspect in the sound beam	
10	S. Lillo I. Giakoni O. Guzmán	Calibration of the echointegrator constant for hake, *Merluccius gayi*	
11	O. Guzmán J. Castillo J. Pineda S. Lillo A. Torres	Calibration of the echointegrator constant for pelagic species in the Chilean seas	
12	O. Guzmán S. Lillo	Calibration of the echointegrator constant for the Antarctic krill, *Euphausia superba*	
15	H.U. Thiel	The digital data acquisition and preprocessing system used on RV "Walther Herwig" during FIBEX	
16	H.U. Thiel	Method and procedure used during FIBEX on board RV "Walter Herwig" to calibrate the acoustic system	
17	R. Person E. Marchal T. Therre J. Berthe	Systeme d'échointegration numérique pour l'évolution des stocks "AGENOR"	FC [3/]
23	M. Azzali	Regarding the possibility of relating echo signal features to classes of marine organisms: tests carried out in the north and middle Adriatic Sea	
25	M. Furusawa K. Ishii Y. Miyanohana	Simultaneous calibration method for precise measurements of target strength of fish and attenuation of sound by schooled fish	

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27	T. Sasakura H. Shiraishi H. Iino K. Minohara	Echo sounder for fish stock assessment	FC[3/]
28	B.P. Pasaribu	Acoustic target strength of fish model targets	Japan[4/]
29	M.A. Do	Design of a microprocessor-based vertical CTFM sonar for use in quantitative assessment of fish populations	
30	A. Dommasnes	Stock size and mortality estimates for Barent Sea capelin, based on acoustic methods	
34	I. Røttingen	Intercalibration of echointegrators on multi-ship surveys	
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56	A. Borud T.W. Hansen S.O. Johannessen	An echosounder signal simulator for hydro-acoustic survey design and training	
57	A. Orłowski	Comparison of the value of target strength per kilogram for different species and areas on the base of calibration and echointegrator indications by bottom trawling results	

Paper No.	Authors	Title	Subsequent Publication
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60	O. Moura G.A. dos Santos	Acoustic calibration with live pilchard and trumpet fish	
61	O. Moura G.A. dos Santos	The results of echointegrator surveys for pilchard carried out in Portugese coastal waters in February, April and August, 1981	
62	D. Poreeyanond	Summary of preliminary results from acoustic surveys in the Gulf of Thailand, 1979	
63	K.I. Udanov I.L. Kalikhman W.D. Tesler	A standard procedure for hydroacoustic estimation of the density of marine animals	
65	Z.I. Kizner W.D. Tesler B.R. Zaripov	Construction and analysis of a statistical model of a fish concentration density field	
66	V.A. Protashchuk T.A. Lukashova	Determination of the acoustic scattering. Cross section of Antarctic krill	
70	K.I. Udanov	Finding and quantitative estimation of krill concentrations by hydroacoustic instruments	
71	Z.M. Berdichevsky V.S. Godlevsky V.F. Evdokimov A.S. Ogir	Some device errors in the measurement of echo signal parameters	
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79	E.J. Simmonds S.T. Forbes	A Comparison between theoretical and measured transducer equivalent beam angles	
80	J.I. Edwards R.S. Bailey	A review of acoustic surveys for sprats in the western North Sea	
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85	T.Y. Lee	A microprocessor-controlled calibrator for time-varied-gain receivers used in acoustic survey systems	

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89	J.R. Dunn	The absolute acoustic calibration of table-tennis balls as standard targets	
90	J. Burczynski M. Lamboeuf S. Bencherifi	Results of calibration on live sardine and trumpet fish in FAO/Norwegian project in Casablanca	
93	A. Elminowicz M. Lamboeuf S. Bencherifi M. Chbani	Application of various methods for determination of calibration constants in FAO/Norwegian project in Morocco	
95	E.P. Nunnallee N.J. Williamson	Acoustic - trawl surveys of spawning walleye pollock, Theragra chalcogramma in the Gulf of Alaska in 1980 and 1981	
100	P.H. Dahl O.A. Mathisen	Measurements of fish directivity at high frequencies	U.S.A.[7]
101	D.R. Gunderson G.L. Thomas P.J. Cullenberg	Combining sector scanning sonar and echosounder data from acoustic surveys	
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116	J.D.R. Bayona	General standards of acoustic assessment systems suitable for use in developing countries	FC[3]

1/ ICES - To be published in Rapp.P.-V.Réun.CIEM, 184 (in preparation)

2/ Canada - Published as follows:

Dickie, L.M., R.G. Dowd and P.R. Boudreau, An echo counting and logging
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3/ FC - To be published in an FAO Fisheries Circular, edited by R.B. Mitson, in 1984

4/ Japan - Published as follows:

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5/ Norway - Published under the same title in Fiskeridir.Skr.(Havunders.), 17:335-46

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7/ U.S.A. - Published as follows:

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Copies of unpublished papers should be obtained directly from the authors. Requests for copies of the original papers Nos. 4, 90 and 116 may be sent to S.C. Venema, Marine Resources Service, Fisheries Department, FAO, 00100 Rome, Italy.

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